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# FUELS AND LUBRICANTS INFLUENCE ON TURBINE ENGINE DESIGN AND PERFORMANCE

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Air Force Aero Propulsion Laboratory

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The "Fuels and Lubricants Influence on Turbine Engine Design and Performance" (FLITE) program was a study to evaluate the influence of fuel temperature limits and engine lubricant temperature limits on installed interceptor performance at the airframe subsystem and engine component level. Engine cycles, representative of technology levels necessary to provide high Mach, steady-state cruise capability in the 1980 time period, were selected. Definition of these concepts permitted evaluation of engine performance as a

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function of fuel and lubricant properties and temperature limitations. Installed performance increments then were determined for advanced interceptors using takeoff gross weight in a fixed mission role as the primary figure of merit. This allowed a measure of the relative performance significance of airframe subsystem and engine component design changes. The relative allotment of available fuel heat sink between engine and airframe was also investigated to determine the primary factors affected by fuel interface temperature which may influence aircraft performance, and to provide meaningful design guidance for future systems application. Results of the program indicate that JP-5/8 fuel and MIL-L-27502 lubricant/hydraulic fluid meet the minimum requirements for a Mach 3+ interceptor while a fuel with JP-7 thermal stability and a 500°F ester lubricant/hydraulic fluid are recommended for advanced aircraft systems in the Mach 4+ category. Above a minimum level the influence of bulk oil temperature has only secondary influence on interceptor performance. The use of precooled fuel provides an attractive option to achieve a direct reduction in aircraft size and weight. The key factor to the future success of advanced aircraft/engine systems is the integrated systems approach to thermal management.



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## FOREWORD

This report was prepared by the Advanced Engineering and Technology Programs Department, Aircraft Engine Group, of the General Electric Company, Evendale, Ohio, for the United States Air Force Aero Propulsion Laboratory (SFL), Air Force Systems Command, on Contract Number F33615-71-C-1512, Project Number 3048 "Fuels, Lubrication, and Fire Protection," Task Number 304805 "Aero Propulsion Fuels," and Task Number 304806, "Aerospace Lubrication." Mr. K.L. Berkey (SFL) monitored the program for the Air Force with the assistance of Capt. W.L. Noll (SFF) and Mr. D.J. Campbell (TBP). The inclusive dates of overall program activity were April 1971 to May 1973.

This document is the Final Technical Report covering the Fuels and Lubricants Influence on Turbine Engine Design and Performance. The study was conducted by the Advanced Engineering and Technology Programs Department (AE&TPD), Mr. Morris A. Zipkin, General Manager. Technical direction of the study program was the responsibility of Mr. Ivan E. Sumey, Manager of Systems, Lubes and Drives (Advanced Fans and Compressors). Overall program management of the study program was the responsibility of Mr. Albert F. Schexnayder, Manager of Subsystems Programs (AE&TPD), with direct program management responsibility delegated to Richard A. Monteferrante, Applications and Requirements Engineer. Other principal investigators during the two year program were: J.C. Dors, J.F. Durcan, E. Elovic, W.A. Fasching, C.N. Gray, D.B. Hester, E.H. Kissel, E.J. Knoll, E.C. Remmell, T.E. Russell, A.A. Saunders, M.W. Shayeson, and M.A. Smith. Airframe coordination was obtained via subcontract with the McDonnell Aircraft Company, under the direction of Mr. James M. Sinnett, Systems Integration Engineer. Other principal MCAIR investigators were: J.E. Augustus, M. Lemon, R.E. Mattes, T.R. Slaten, and J.E. Stone.

This report was submitted by the author on 1974 April 16.

This Technical Report has been reviewed and is approved.

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## ABSTRACT

The "Fuels and Lubricants Influence on Turbine Engine Design and Performance" (FLITE) programs was a study to evaluate the influence of fuel temperature limits and engine lubricant temperature limits on installed interceptor performance at the airframe subsystem and engine component level. Engine cycles, representative of technology levels necessary to provide high Mach, steady-state cruise capability in the 1980 time period, were selected. Definition of these concepts permitted evaluation of engine performance as a function of fuel and lubricant properties and temperature limitations. Installed performance increments then were determined for advanced interceptors using take-off gross weight in a fixed mission role as the primary figure of merit. This allowed a measure of the relative performance significance of airframe subsystem and engine component design changes. The relative allotment of available fuel heat sink between engine and airframe was also investigated to determine the primary factors affected by fuel interface temperature which may influence aircraft performance, and to provide meaningful design guidance for future systems application. Results of the program indicate that JP-5/8 fuel and MIL-L-27502 lubricant/hydraulic fluid meet the minimum requirements for a Mach 3+ interceptor while a fuel with JP-7 thermal stability and a 500° F ester lubricant/hydraulic fluid are recommended for advanced aircraft systems in the Mach 4+ category. Above a minimum level the influence of bulk oil temperature has only secondary influence on interceptor performance. The use of precooled fuel provides an attractive option to achieve a direct reduction in aircraft size and weight. The key factor to the future success of advanced aircraft/engine systems is the integrated systems approach to thermal management.

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## LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| $A_4$ | High pressure turbine first stage nozzle inlet area |
| $A_8$ | Core exhaust nozzle throat area |
| $A_9$ | Core exhaust nozzle exit area |
| $A_{18}$ | Bypass duct nozzle throat area |
| $A_{25}$ | Bypass duct inlet area |
| A/C | Aircraft |
| Act. | Actuator |
| Accel | Acceleration |
| AFBMA | Anti-Friction Bearing Manufacturers' Association |
| allow | Allowable |
| Alt | Altitude |
| ASTM | American Society for Testing and Materials |
| avail | Available |
| B | Boost pump |
| $B_{10}$ | Bearing fatigue life at which 90% of a given set of bearings will achieve or exceed |
| BOT | Bulk oil temperature |
| $B_s$ | Isentropic tangent bulk modulus |
| $B_t$ | Isothermal tangent bulk modulus |
| Btu | British thermal unit |
| Cal | Calories |
| C&A | Controls and accessories |
| Cent. | Centrifugal |
| C.G. | Center of gravity |
| Comp. | Compressor |
| CONUS | Continental United States |

LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

| | |
|---|---|
| $C_p$ | Specific heat at constant pressure |
| cs | Centistokes |
| $C_v$ | Specific heat at constant volume |
| CVM | Consumable vacuum melt |
| D, Dia. | Diameter |
| DES | Design |
| ECS | Environmental control system |
| E-H/M | Electrohydromechanical |
| FPS | Fluid power system |
| °F | Degrees Fahrenheit |
| g | Gravitational constant |
| GE | General Electric Company |
| gm | Gram |
| gpm | Gallons per minute |
| H | Enthalpy |
| h | Heat transfer coefficient |
| HFPO | Hexafluoropropylene epoxide |
| Hg | Mercury |
| hp | Horsepower |
| HV | Heating value |
| H-X | Heat exchanger |
| ID | Inside diameter |
| IGV | Inlet guide vane |
| in | Inches |
| $in^2$ | Square inches |

LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

| | |
|---|---|
| $in^3$ | Cubic inches |
| IOC | Initial operational capability |
| K | 1,000 |
| °K | Degrees Kelvin |
| knts | Knots |
| L | Length |
| L&S | Lube and Scavenge |
| lb | Pounds |
| L/D | Lift to drag ratio |
| LE | Leading edge |
| Ln | Natural Logarithm |
| LP | Low pressure |
| LVDT | Linear variable differential transformer |
| M | Mach |
| max | Maximum |
| MB | Main burner |
| MCAIR | McDonnell Aircraft Company |
| MD | Design Mach number |
| min | Minute |
| mm | Millimeters |
| NPSP | Nonpositive suction pressure |
| O/B | Overboard |
| OD | Outside diameter |
| OWE | Operating weight empty |
| P | Pressure regulator |

| | |
|---|---|
| $P_1$ | Engine inlet total pressure |
| $P_2$ | Fan inlet total pressure |
| $P_3$ | Compressor discharge total pressure |
| $P_8$ | Core exhaust nozzle throat total pressure |
| $P_{14}$ | Bypass duct inlet total pressure |
| pph | Pounds per hour |
| pps | Pounds per second |
| PS | Power setting |
| psf | Pounds per square foot |
| psi | Pounds per square inch |
| psia | Pounds per square inch absolute |
| psid | Pounds per square inch differential |
| psig | Pounds per square inch gauge |
| PTO | Power take-off |
| $P_{T0}$ | Freestream total pressure |
| $P_{T2}$ | Total pressure at engine face |
| Q | Heat rejection |
| q | Dynamic pressure |
| °R | Degrees Rankine |
| Ref | Reference |
| R/J | Ramjet |
| rpm | Revolutions per minute |
| Scav | Scavenge |
| sec | Second |
| SFC | Specific fuel consumption |

LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

| | |
|---|---|
| SL | Sea level |
| SLS | Sea level static |
| Spec | Specification |
| SST | Supersonic transport |
| T | Temperature |
| $T_1$ | Engine inlet total temperature |
| $T_3$ | Compressor discharge total temperature |
| $T_4$ | High pressure turbine first stage nozzle inlet total temperature |
| $T_8$ | Core exhaust nozzle throat total temperature |
| $T_{14}$ | Bypass duct inlet total temperature |
| $T_{18}$ | Bypass duct exhaust nozzle throat total temperature |
| $T_{41}$ | High pressure turbine rotor inlet total temperature |
| $T_{A1}$ | Sump pressurization air fuel/air cooler inlet temperature |
| $T_{A2}$ | Sump pressurization air fuel/air cooler discharge temperature |
| TASP | Sump pressurization air temperature |
| TBLD3 | Compressor third stage bleed air temperature |
| $T_i$ | Titanium |
| T/J | Turbojet |
| T/O | Takeoff |
| TOGW | Take-off gross weight |
| Turb. | Turbine |
| VSV | Variable stator vane |
| $W_1$ | Engine inlet airflow |
| $W_{1R}$ | Engine inlet corrected airflow |

## LIST OF ABBREVIATIONS AND SYMBOLS (Concluded)

| | |
|---|---|
| $W_{2C}$ | Compressor inlet airflow |
| $W_8$ | Core exhaust nozzle airflow |
| $W_{18}$ | Bypass duct exhaust nozzle airflow |
| $W_{25}$ | Compressor inlet airflow |
| $W_a$ | Airflow |
| WAIR | Sump pressurization air fuel/air cooler airflow |
| $WC_8$ | Turbojet exhaust nozzle cooling airflow |
| $WC_{26}$ | Ramjet duct main burner cooling airflow |
| $WC_{28}$ | Ramjet duct exhaust nozzle cooling airflow |
| WFC | Core fuel flow |
| WFD | Bypass duct fuel flow |
| WFT | Total fuel flow |
| $W_t$ | Weight |
| ° | Degrees |
| % | Percent |
| $\alpha$ | Angle of attack |
| $\gamma$ | Ratio of specific heats |
| $\Delta$ | Increment |
| $\nu$ | Kinematic viscosity |

# SECTION I

## INTRODUCTION

Advanced interceptor systems, responsive to the anticipated Continental United States (CONUS) defense needs in the 1980's, are representative of a new generation of aircraft capable of operation in the high speed elevated temperature environment. In order to provide the excellent flight performance and adequate thermal protection systems necessary for timely aircraft introduction and mission success, several major systems and program technical issues are currently being investigated on an exploratory and advanced development basis. One of these key issues is advanced engine design and cycle definition. As a parallel step, it becomes pertinent to address the performance and thermal capabilities provided through use of selected fuels and lubricants, identify the impact of fuel and lubricant selection on engine and vehicle performance, and assess the impact of variations in engine/airframe interface temperatures and maximum fluid temperatures in the engine.

This report summarizes a two year study program performed by the General Electric Company (GE) under Air Force Contract F33615-71-C-1512 entitled, Fuels and Lubricants Influence on Turbine Engine Design and Performance (FLITE). The objective of this program was to provide a measure of installed performance capabilities for high speed advanced turbine engine cycles as a function of fuel and lubricant design temperature limitations and material capabilities.

The study approach was to match advanced engine and aircraft designs for each of two defined mission profiles using specific fluid capabilities as a design baseline. The resulting engine airframe designs were then modified to exploit the advantages of candidate fluids and identify potential improvements. The mission analysis included the use of two families of fuels and four lubricants. Results were measured in terms of engine weight, engine performance improvement, and aircraft take-off gross weight (TOGW) on a fixed mission basis.

In support of the General Electric Company, the McDonnell Aircraft Company (MCAIR) was employed as a subcontractor. Engine cycles, representative of technology levels corresponding to Mach 3+ and Mach 4+ capabilities in the 1980 time period were selected to permit evaluation of engine performance as a function of fuel and lubricant properties and temperature limitations.

This program fulfilled all the desired objectives and identified the relative performance capabilities associated with current fuels and lubricants. In addition, several development alternatives are identified to provide improvements in air defense capabilities for the next generation of advanced manned interceptors.

## SECTION II

## SUMMARY

This report presents the results of the two year effort on the Fuels and Lubricants Influence on Turbine Engine Design and Performance Program (FLITE) and represents the cooperation of the General Electric Company (GE) and the McDonnell Aircraft Company (MCAIR) in the determination of the applicable engine and aircraft performance criteria. Presented herein are the results of the Mach 3+ interceptor studies (Mission A) and the Mach 4+ (Mission B) interceptor studies.

MISSION A

The GE16/FLITE engine was selected for use in the Mach 3+ mission interceptors. This engine is a duct-burning turbofan with a low bypass ratio, moderate cycle pressure ratio, and high turbine inlet temperature.

Fuels representing the thermal stability classes of JP-5/8 and JP-7 were evaluated at a maximum engine/airframe fuel interface of 250° F in conjunction with a matrix of four engine lubricants to determine their effects on engine weight and performance. These fluids and projected temperature capabilities are presented below:

GE16/FLITE FLUID TEMPERATURE LIMITATIONS

| Fuels | Temperatures (° F) |
|---|---|
| JP-5/8 | 325 |
| JP-7 | 700 |
| **Lubricants** | |
| Mil-L-27502 | 425 |
| 500° F Ester | 500 |
| Polyphenyl Ether | 575 |
| Perfluorinated Polyether | 650 |

The resulting engine performance and weights were then used to perform the interceptors in the selected flight profile. The lightest study interceptors were obtained with the JP-7 class fuel and either the 500° F ester or the polyphenyl ether lubricants. However, the use of JP-5 resulted in a weight penalty of only 950 lb, which when coupled with the relative cost and availability of JP-5/8 as compared to JP-7, provided the most practical concept.

Interceptor weight variations achieved through the use of the four lubricants were of second order effect. The perfluorinated polyether was the only lubricant which resulted in a significant weight penalty of approximately 400 pounds. The increase in weight for perfluorinated polyether results from engine lubrication and fluid power system design changes to accommodate its low bulk modulus and high vapor pressure. The weight differences for the other lubricants are approximately 50 pounds, which when compared to the 70,000 pound class interceptor, cannot be considered sufficient to select a "best" lubricant on a bulk temperature basis. Final selection would, therefore, require detailed investigation of lubrication and hydraulic system design variables as a function of fluid properties.

The use of fuel recirculation to the aircraft main feed tanks to prevent engine system overtemperature conditions was established as a practical concept. With minimum complexity involved, this technique permits the transition from high Mach number cruise to flight idle-descent without violating engine system fluid thermal stability criteria.

Additional interceptors were evaluated for the Mach 3+ mission to assess the effects of higher interface temperatures and to assess the benefits of precooled fuel. By using an ambient temperature JP-7 class fuel and increasing the interface temperature to 350° F, sufficient fuel heat sink is available to permit considerable simplication of the aircraft environmental control system (ECS) and elimination of ECS ram air. The resulting interceptor indicates a weight savings of 260 pounds relative to the use of JP-7 at an interface temperature of 250° F.

Use of precooled fuel permits additional environmental control system simplification through the elimination of the air cycle refrigeration package and the use of a direct fuel heat sink. In conjunction with a higher fuel density, this results in a 4500 lb reduction in TOGW when compared to the JP-7, 250° F interface temperature interceptor.

MISSION B

The same matrix of fuels and lubricants is evaluated in Mission B as in Mission A. However, the fuel temperature capabilities in the engine were increased to 475° F for JP-5/8 and 1000° F for JP-7 to reflect a later projected initial operational capability (IOC) date, and the anticipated availability of engine cleaning techniques and improved fuel properties. The 1000° F limit for JP-7 also reflects design of the engine system to minimize fuel residence time at temperature, thereby controlling total deposit formation. The influence of engine/airframe fuel interface temperature on both airframe subsystem and engine performance was determined for JP-5 at 150° F and 250° F and for JP-7 at 250° F and 350° F. The lightest study interceptor from the matrix of fuel, lubricant, and interface combinations considered is obtained with JP-7 fuel, polyphenyl ether engine lubricant, and a 350° F fuel interface temperature. This interceptor is 2300 lb lighter than the JP-5/8 fueled, 150° F fuel interface temperature concept. All of the Mission B interceptors are in the 80,000 lb class TOGW range.

A trend of decreasing interceptor weight with increasing fuel interface temperature was noted for both the JP-5/8 and JP-7 fueled concepts. This trend indicated the benefits of maximizing the airframe fuel heat sink allotment relative to that of the engine within the particular engine inlet temperature limitations. The engine inlet temperature limitations would be based on engine fuel pump inlet requirements, material temperature limitations, and lubricant/hydraulic fluid constraints.

Lubricant selection was of second order effect for Mission B. Perfluorinated polyether was the only lubricant which resulted in significant interceptor weight penalties (approximately 1200 lb). The engine fuel recirculation concept was also effectively applied during the flight idle-descent phases of Mission B.

Additional Mission B evaluations were performed to evaluate the effects of (1) using precooled fuel and (2) cooling engine inlet structure using the fuel heat sink. Precooled fuel provides significant reductions in ECS weight. In conjunction with increased fuel density, this results in a TOGW reduction of 3000 lb when compared to the lightest ambient fueled configuration. This illustrates the benefits which may be obtained through the use of precooled fuel. Cooling the engine inlet structure would have significant impact on inlet weight if a conventional high temperature structural material were used in its fabrication.

Mach 3+ and Mach 4+ class systems are attainable with current fuel and lubricant state of the art using the advanced engine technology noted herein. Use of airplane size and weight as a figure of merit for fixed mission performance indicates that lubricant selection effects are second order as compared to the fuel selection and variations in allowable fuel temperature. Significant reductions in ECS weight and complexity can be realized by allowing higher engine/airframe fuel interface temperatures, thereby providing more efficient thermal management of fuel heat sink.

A JP-5/8 class of fuel is recommended for the Mach 3+ interceptor and a JP-7 class of fuel is recommended for the Mach 4+ interceptor. No specific lubricant recommendations can be made on the basis of the weight sensitivities. Lubricant selection is more appropriately based on a wider view of relative operational service life and cleaning/recycle requirements attendant to a specific engine design.

The results noted above can also be applied to near term operational systems. Higher environmental and secondary cooling loads associated with advanced avionics and control technologies, combined with improved engine efficiencies and lower fuel flows for evolving Air Force weapon systems, draws attention to fuel thermal stress limits. The primary factor is heat addition per pound of fuel, as exemplified by current specification limits for engine airframe interface fuel temperatures. It is recommended that the installed performance trends and heat sink utilization payoffs noted herein be investigated in the context of near term systems application for potential modification of specification design limits.

## SECTION III

## BASELINE DEFINITIONS

### A. Interceptor Sizing and Performance

In order to determine interceptor design and performance characteristics for the FLITE program, initial sizing studies were performed for the Mach 3+ and Mach 4+ systems. This allowed determination of initial aircraft and engine size envelopes for design comparisons, and enabled determination of acceleration/climb, cruise, and idle descent characteristics.

Interceptor mission performance goals and sizing parameters were based on capable manned interceptor response to a projected CONUS threat in the 1980's. Key elements of the mission from an interceptor design standpoint were rapid acceleration, supersonic cruise, and extended mission radius. The interaction of the threat characteristics, CONUS early warning and advanced interceptor capability enabled definition of the mission profiles. This, in turn, provided a rational approach to the determination of desired aircraft mission performance and sizing characteristics. The systems thus established were used as a basis for determination of subsequent performance sensitivities using specific engine and subsystems data generated from the fuel and lubricant study matrix.

### B. MISSION A BASELINE

#### B.1 Engine Design

##### General Description

The GE16/FLITE-1A is a duct-burning turbofan engine and represents an advanced engine embodying technology of the early 1980 time period. The basic engine is sized for 277 pps corrected air flow at sea level static, standard day conditions at the maximum engine power setting (26,160 lb thrust).

A cross section of the engine is shown in Figure 1. This engine is a low bypass ratio, moderate cycle pressure ratio engine and features high turbine inlet temperature. The core consists of a multistage compressor driven by a single stage turbine. The low pressure system consists of a two-stage fan and a two-stage turbine. The fan design incorporates variable inlet guide vanes to provide good efficiency and stability characteristics throughout the operating regime. The duct burner is a two stage design capable of fuel augmentation of the fan stream. It is staged to yield high efficiency for the medium augmentation range. The exhaust nozzle is selected to reduce the afterbody drag of the large diameter duct-burning engine, being sized to yield the highest possible ratio of exit to maximum engine diameter, resulting in a low boattail angle and projected afterbody area. The exhaust nozzle was also designed for good overall performance with special emphasis on subsonic cruise, transonic acceleration, and supersonic cruise. It is a confluent flow design with a fixed core throat area and a variable duct flow throat. A cylindrical shroud provides the required internal exit area variation. At low nozzle pressure ratios the shroud is retracted, being translated aft as pressure ratio increases.

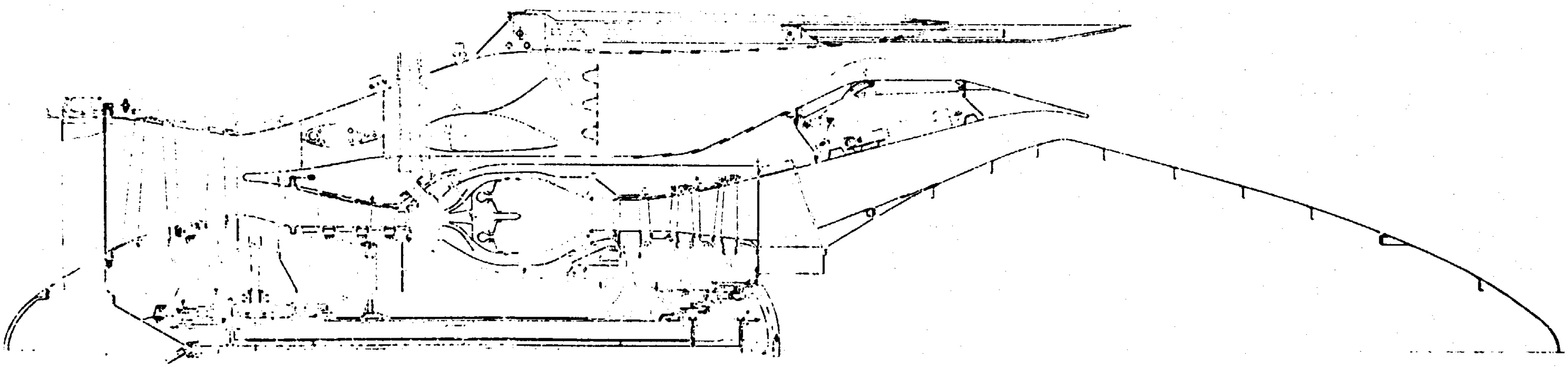


Figure 1. GE16/FLITE-1A Engine Cross Section.

The engine outline drawing is presented in Figure 2. The estimated maximum dry weight of the GE16/FLITE-1A engine is 3200 pounds. This weight represents the complete engine in that all of the items normally required for handling, installation, operation, and monitoring of the engine are included. The quoted weight also includes the following specific installation features:

- Self-contained oil tank including remote filling, internal coolers, and oil level indication
- Engine fuel and power control system
- Fan inlet guide vane anti-icing
- Accessory gearbox mounted on the fan frame with power takeoff to drive aircraft-mounted accessories

The design speed (100%) of the core is 13,300 rpm while the design speed of the low pressure system is 8,680 rpm.

For scaling purposes for use in aircraft sizing thrust, and fuel flow vary directly with air flow while rotor speeds scale inversely with the square root of airflow. Weight, length, and diameter can be scaled between -20 percent and +30 percent of the sea level static maximum airflow with the following equations:

$$W_{t_2} = W_{t_1} \left(\frac{W_{a_2}}{W_{a_1}}\right)^{1.2} \qquad (1)$$

$$D_2 = D_1 \left(\frac{W_{a_2}}{W_{a_1}}\right)^{0.5} \qquad (2)$$

$$L_2 = L_1 \left(\frac{W_{a_2}}{W_{a_1}}\right)^{0.5} \qquad (3)$$

Fuel Delivery System

The GE16/FLITE-1A baseline fluid system schematic is shown in Figure 3. This system consists of the fuel delivery system coupled through heat exchangers to the lubrication and fluid power systems.

The fuel delivery system receives fuel from the aircraft fuel tank boost pumps at between 15 and 40 psia depending upon altitude. The engine fuel pumps then increase the fuel pressure to a level sufficient to overcome all system pressure losses and to inject the fuel into the engine combustors. The high pressure fuel is also utilized as the hydraulic power source for the stator actuators used to position the variable stators.

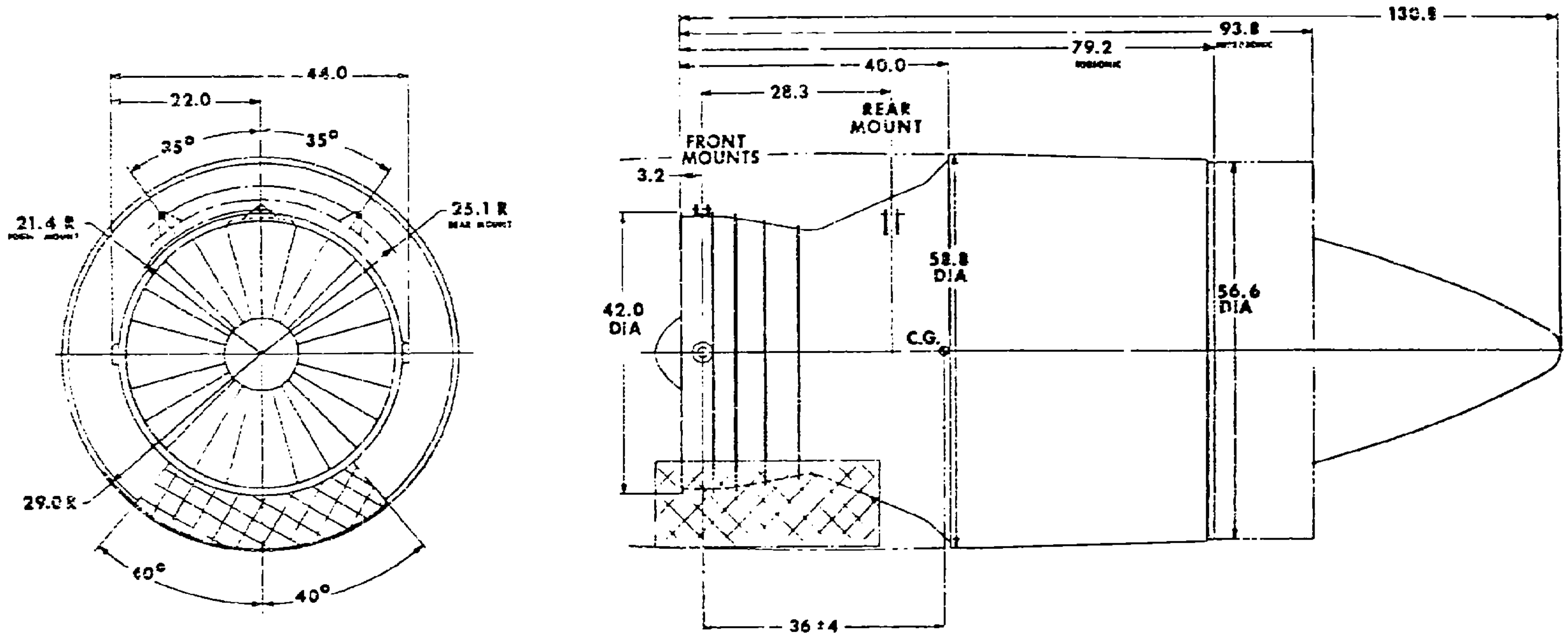



Figure [illegible]. GE16/FLITE-2A Outline Drawing.

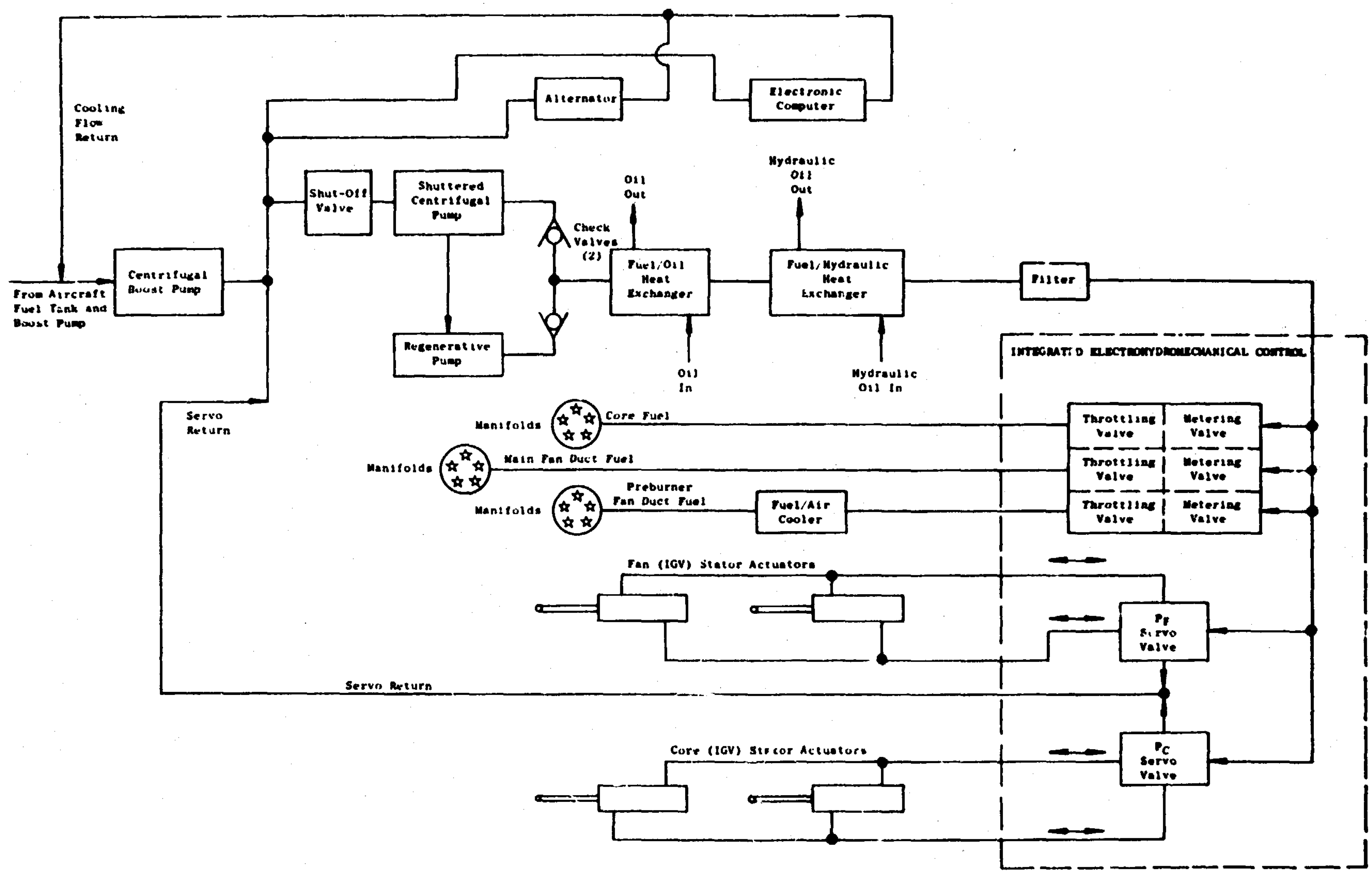



Figure 3. GE16/FLITE-1A Fuel Delivery System Schematic.

The electronic control provides the schedules for the variable stator positions and the metered fuel flow to the engine. During steady state operation conditions, the control system meters fuel flow to the engine combustors by means of an integrating speed control in order to maintain precise engine speed. During transient operation, engine fuel flow is limited by acceleration and deceleration fuel flow schedules to prevent overtemperature, overspeed or burner blowout. The fuel control system also incorporates overrides for engine protection, including core rotor speed and turbine blade temperature.

The engine fuel is the prime source of heat sink for cooling engine and aircraft components. In the engine the fuel is used to cool the control alternator, the electronic computer, the boost pump and the main fuel pumps. In addition, the fuel absorbs the heat generated in the lubrication and fluid power systems and the heat absorbed from the system environment. Since these heat sink requirements strain the fuel heat absorption capacity over portions of the mission profile, it was an objective of this program to specify the fuel delivery system components around a minimum heat generation criterion.

The throttling type fuel control was selected because of its high efficiency and low thermal input to the fuel. The fuel flow control system functions by throttling the flow and maintaining a fixed back pressure on the centrifugal pump. The centrifugal boost pump provides small size and weight and proven reliability. This low speed pump can operate at low input pressures from the aircraft boost pump without cavitation, and is capable of supplying sufficient pressure to prevent cavitation in the main high pressure pumps. The regenerative pump has the ability to supply relatively high pressure fuel at low shaft speeds and fuel flows during engine starts. The regenerative pump is lightweight and can be flow regulated by throttling. The fuel delivery system is designed to utilize the regenerative pump only during engine starts. As engine speed approaches idle, the shuttered centrifugal pump takes over with the inlet to the regenerative pump being shut off and the pump casing drained.

The shuttered centrifugal pump was selected because of its broad flow turn down ratio. A flow turndown ratio of at least 150:1 is possible with a shuttered centrifugal pump. Since the major contributor to the use of the fuel heat sink in the fuel delivery system is the main fuel pump, utilization of the shuttered centrifugal pump design prevents excessive thermal stressing of the fuel during the return cruise portion of the mission. Closing of the shutter at low fuel flows prevents recirculation in the pump and as a result significantly reduces the power losses. Figure 4 shows the pump characteristics of the GE16/FLITE-1A main fuel pump. By closing the shutter at flow rates below approximately 10 percent of the maximum fuel flow, the major portion of the return leg of the mission is spent in closed shutter operation. Figure 5 shows the variation in the fuel temperature at the core engine nozzles for open and closed shutter operation and indicates the reduction in fuel temperature achieved by closing the shutter.

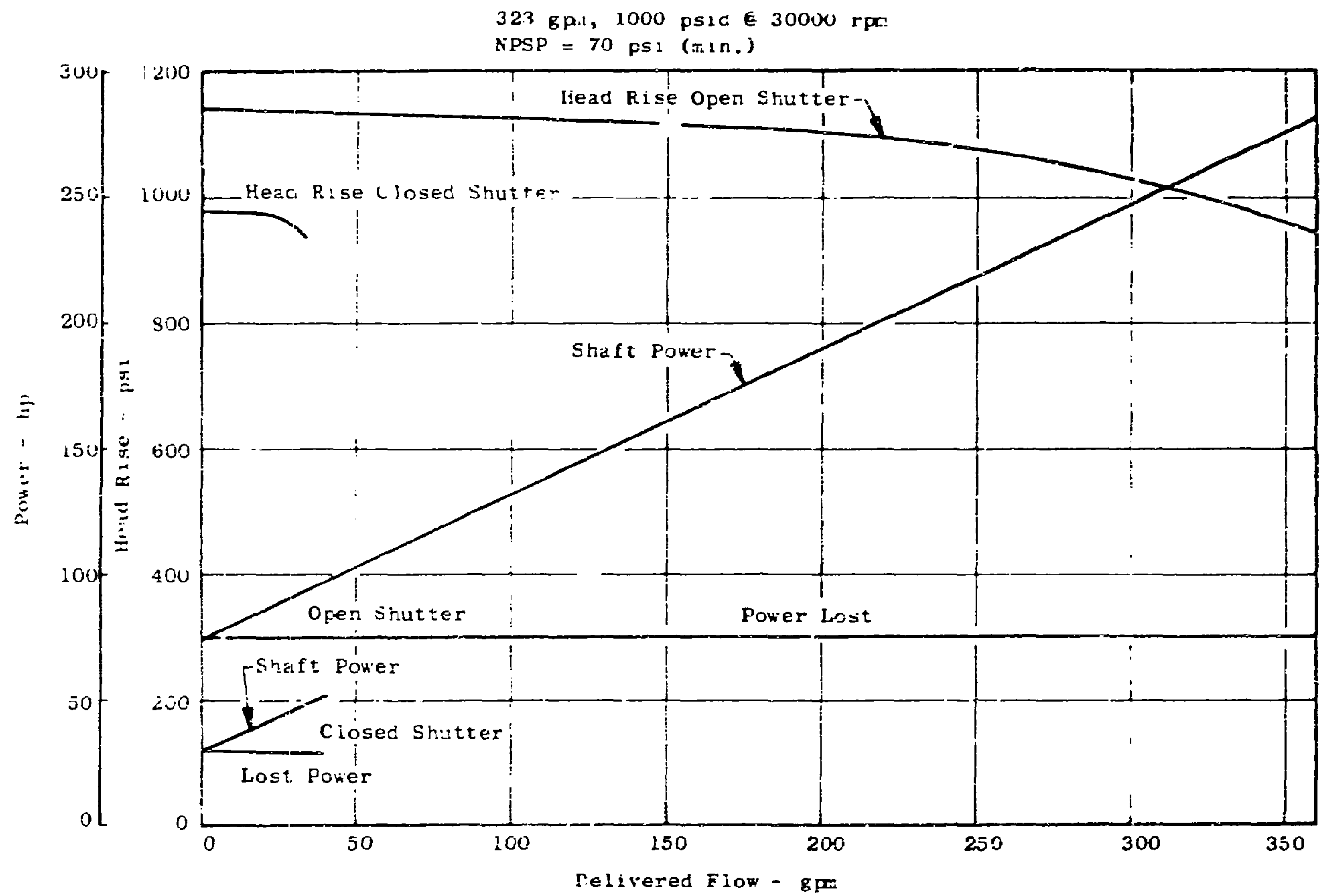



Figure 4. GE16/FLITE-1A Main Fuel Pump Characteristics.

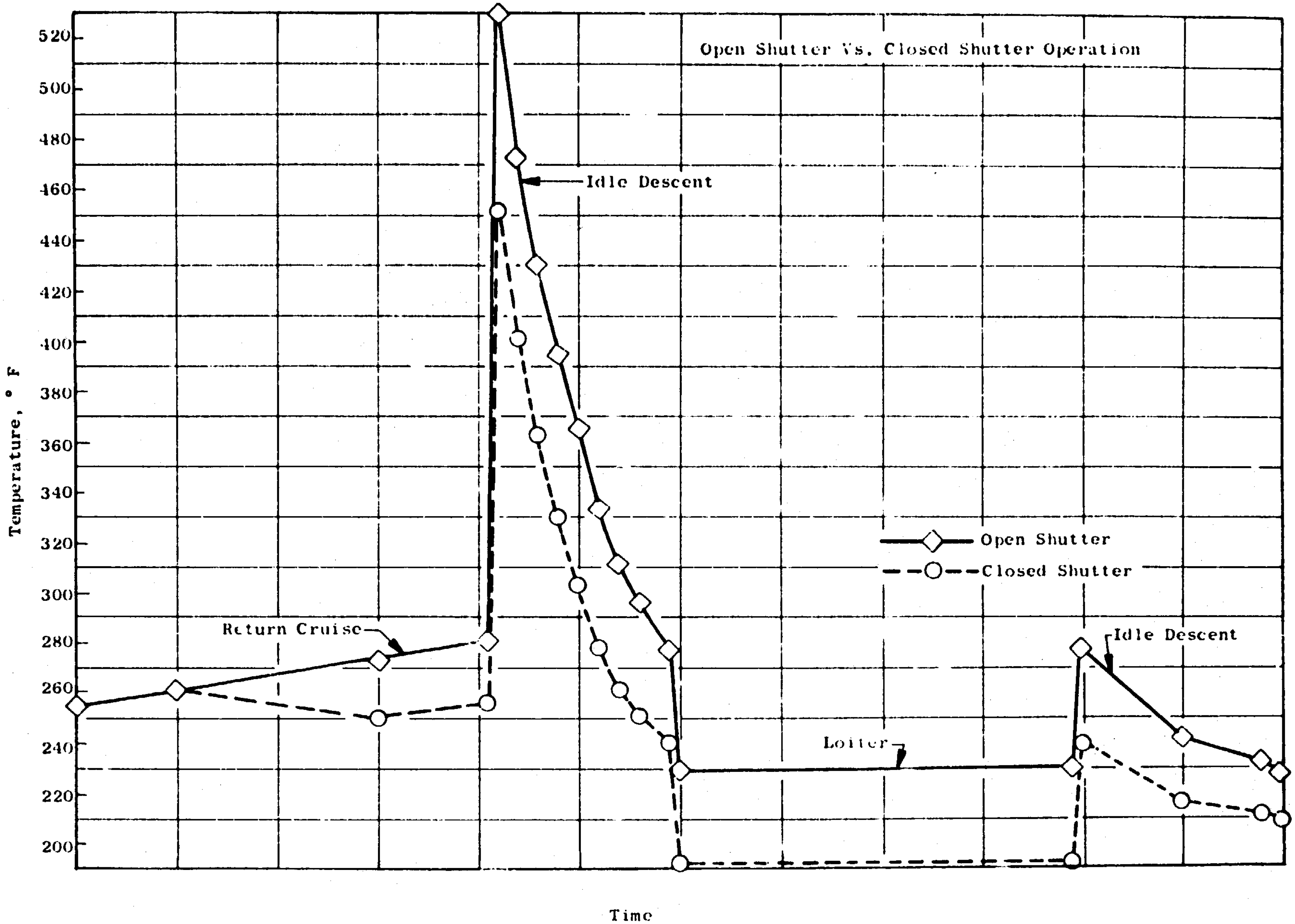



Figure 5. Variation in Fuel Temperature at the Core Engine Nozzles for Open and Closed Shutter Operation.

Thermal insulation is utilized on all fuel delivery system fluid lines exposed to the engine environment. The insulation was selected to provide the maximum temperature reduction based on location of fluid line in the environment. For maximum altitude and Mach number, the insulation design selected results in approximately an 18° F temperature rise due to environmental heating at the most remote fuel nozzle. This is about one quarter of the temperature rise which would occur with no thermal insulation. This protection is provided at the penalty of a fuel delivery system weight increase of approximately 8.5 pounds.

The critical cooling region for the engine systems occurs during idle descent where the engine fuel inlet temperature reaches a maximum of 200° F. This 200° F fuel inlet temperature, along with the engine heat sink requirements, would produce severe overtemperature conditions in the fuel during idle descent and some provisions for additional heat sink capacity are required.

The means chosen to provide additional heat sink capacity was the addition of a fuel recirculation system from the engine fuel control to the aircraft fuel tank. This recirculation system required a modification to the main engine fuel control which involves an additional control function to reroute a specific amount of the total inlet fuel flow to the aircraft fuel tanks at the initiation of idle descent. The initiation of the recirculation fuel flow is a function of throttle angle and fuel temperature level at the engine fuel control. At idle throttle angle positions and when the fuel temperature reaches 300° F, the recirculation system is activated and a portion of the inlet fuel flow is rerouted through a fixed orifice in the engine fuel control to the aircraft fuel tanks. The incorporation of this recirculation system results in a weight penalty of approximately 3 lb to the engine fuel system.

## Engine Lubrication System

A sump area layout for the GE16/FLITE-1A engine is presented in Figure 6 and the lubrication system schematic is shown in Figure 7.

Oil is supplied to the inlet of the lubricant supply element by gravity feed from the oil tank. Oil under pressure is then supplied by the pump to the supply filter, which serves to protect the oil jets from contamination. This filter is equipped with a bypass pressure relief valve which opens at a predetermined pressure differential and allows full oil flow to continue to be supplied to the engine should the filter become plugged. Oil supply pressure to the engine is limited during cold starts by a pressure relief valve which will bypass oil directly to the gearbox if the supply pressure exceeds a preset value. At all pressures less than this value, the entire output from the filter is directed to the engine supply system. A static anti-leak check valve is provided to limit leakage from the tank to the engine to an acceptable level during or after engine shutdown.

A total of 13.5 gpm of oil is supplied to three areas of the engine; the forward or "A" sump, the aft or "B" sump, and the accessory gearbox. The "A" sump is supplied through a pipe in a fan frame strut. The "B" sump is supplied

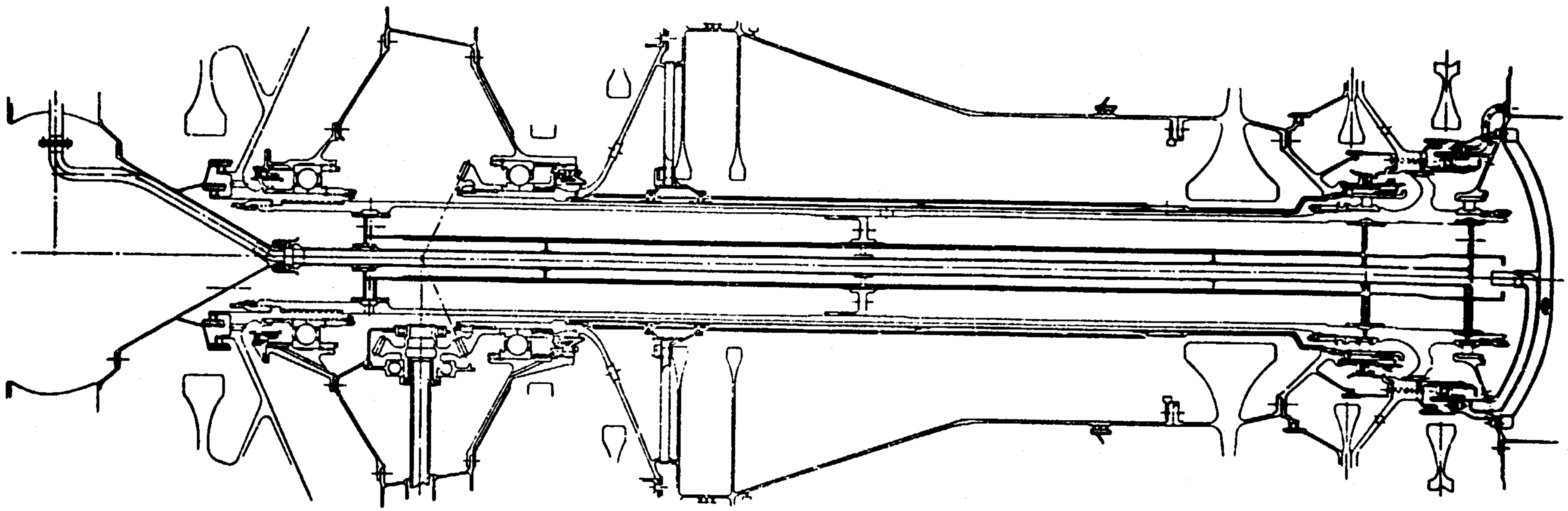


Figure 6. GE16/FLITE-1A Sump Area Layout Drawing.

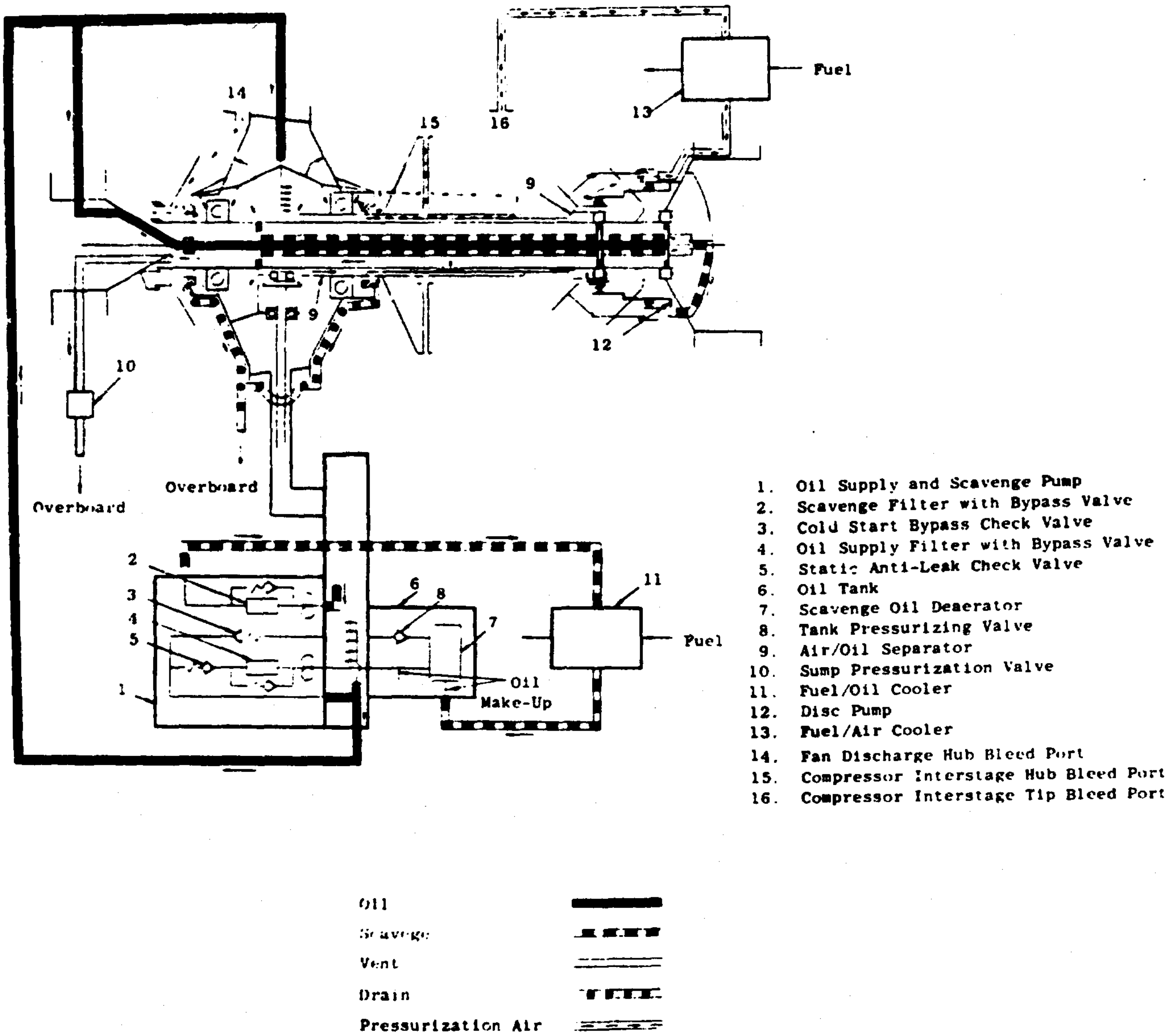



Figure 7. GE16/FLITE-1A Lubrication System Schematic.

by a pipe through a strut in the front frame, the oil being routed through a rotating tube inside the low pressure shaft to the "B" sump where it is centrifugally fed to the bearings. A carbon seal is used to limit oil leakage between the stationary and rotating portions of the oil line. Any oil loss from this seal drains into the "A" sump. The engine oil flow quantity has been sized to provide adequate lubrication of the bearings, gear meshes, and splines and to cool all the system components. The distribution of flow for the baseline engine is shown in Table I.

The "A" sump/inlet gearbox area is scavenged by gravity through the PTO shaft housing to the accessory gearbox. The accessory gearbox is scavenged by a single scavenge pump element and the oil is then routed to the scavenge filter. The scavenge filter contains a bypass valve which allows the oil to bypass the filter element if it becomes plugged by contamination.

Table I.
GE16/FLITE-1A Lubrication System
Design Oil Flow Distribution

| Component | Design Flow (gpm) |
|---|---|
| "A" Sump | 6.65 |
| Inlet Gearbox | 0.85 |
| "B" Sump | 3.65 |
| Accessory Gearbox | 2.35 |
| Total Supply | 13.50 |
| Total Scavenge Capacity | 27.00 |

The oil is then piped to the fuel/oil heat exchanger where the heat generated by the engine is transferred to the fuel. From the heat exchanger, the oil is returned to the tank. The "B" sump is scavenged by a disk pump driven off the low pressure rotor. This pump has a tangential collector in the stationary pump wall to recover a portion of the velocity head. The scavenge oil is then piped inward to the engine centerline and discharged into a rotating scavenge tube which pumps the oil forward to the "A" sump by centrifugal force.

Pressurization air is required to maintain positive flow across the main shaft oil seals into the sumps at all operating conditions. If air is allowed to flow out of a sump through an oil seal, some oil will be carried with it. This oil leakage must be eliminated in order to prevent excessive oil consumption, contamination of the compressor bleed air and possible fire hazard. The pressurization air must simultaneously be at a high enough pressure to isolate the sumps from hot cycle air and at low enough pressure and temperature to provide the life required for the oil seals.

The Number 1 oil seal is pressurized with fan discharge hub bleed air. Pressurization air for the Number 2 oil seal is extracted from the compressor at the second-stage rotor discharge hub. The air flows through the rotor and radially inward through a paddle-wheel inducer. A portion of the air is then directed forward inside the compressor air tube to the Number 2 seal pressurization cavity. The remaining air is directed aft inside the air tube for use in cooling the compressor drum and high pressure turbine forward shaft. The Number 3 and Number 4 oil seal pressurization air is extracted from the compressor at the third-stage exit tip. This air is cooled in a fuel/air heat exchanger and then piped to the Number 4 oil seal pressurization cavity through a strut in the turbine frame. A portion of the air flows through holes in the low pressure turbine stub shaft to pressurize the Number 3 oil seal.

The oil tank is vented to the accessory gearbox. The vent line contains a tank pressurization valve which maintains the tank pressure above sump vent pressure. The increased tank pressure is provided to pressurize the supply pump inlet and to reduce the variation in oil supply quantity to the engine under varying flight conditions. The air flow through this valve is sufficient to maintain tank pressure at altitude. The accessory gearbox is vented to the "A" sump through the hollow PTO shaft. The "A" sump is vented aft through the intershaft space between the high pressure and low pressure rotor shafts and the "B" sump is vented forward through the same intershaft space. The centrifugal field in the gap between the two rotating shafts allows this space to be used effectively as an air/oil separator, with the separated oil being returned to the sump cavities. Midway between the sumps, the vent air flows inward through holes in the low pressure rotor shaft and forward inside the shaft, being piped overboard to ambient pressure through a strut in the front frame. The overboard vent line contains a sump pressurization valve to assure adequate pressure in the sumps for scavenging at altitude.

The accessory drive train was defined based on controls and accessories component power requirements and accessory sizes. Accessory power is taken directly from the high pressure rotor through a set of bevel gears (inlet gearbox) as shown in the sump area layout, Figure 6. Power is transmitted by a radial drive shaft to the accessory gearbox located at the 6 o'clock position on the engine frame. A set of bevel gears is used in the accessory gearbox so that the accessory drives can be mounted parallel to the engine centerline in order to obtain a minimum envelope. Spur gears are used in the remainder of the gearbox. Each gearshaft is supported by a ball and a roller bearing. Carbon face seals with bellows secondary seals are bolted into the gearbox housing to prevent leakage between gearbox oil and each accessory.

Super nitraloy was selected as the material for all of the gears with a minimum design gear life of 36,000 hours. The bearing material is CVM-M50 tool steel with the bearings being sized to give an AFBMA $B_{10}$ life of 8,000 hours. The gearbox housing is manufactured from investment cast 17-4 PH stainless steel and its useful life without repair is designed to be 36,000 hours. A layout of the GE16/FLITE-1A accessory gearbox is presented in Figure 8.

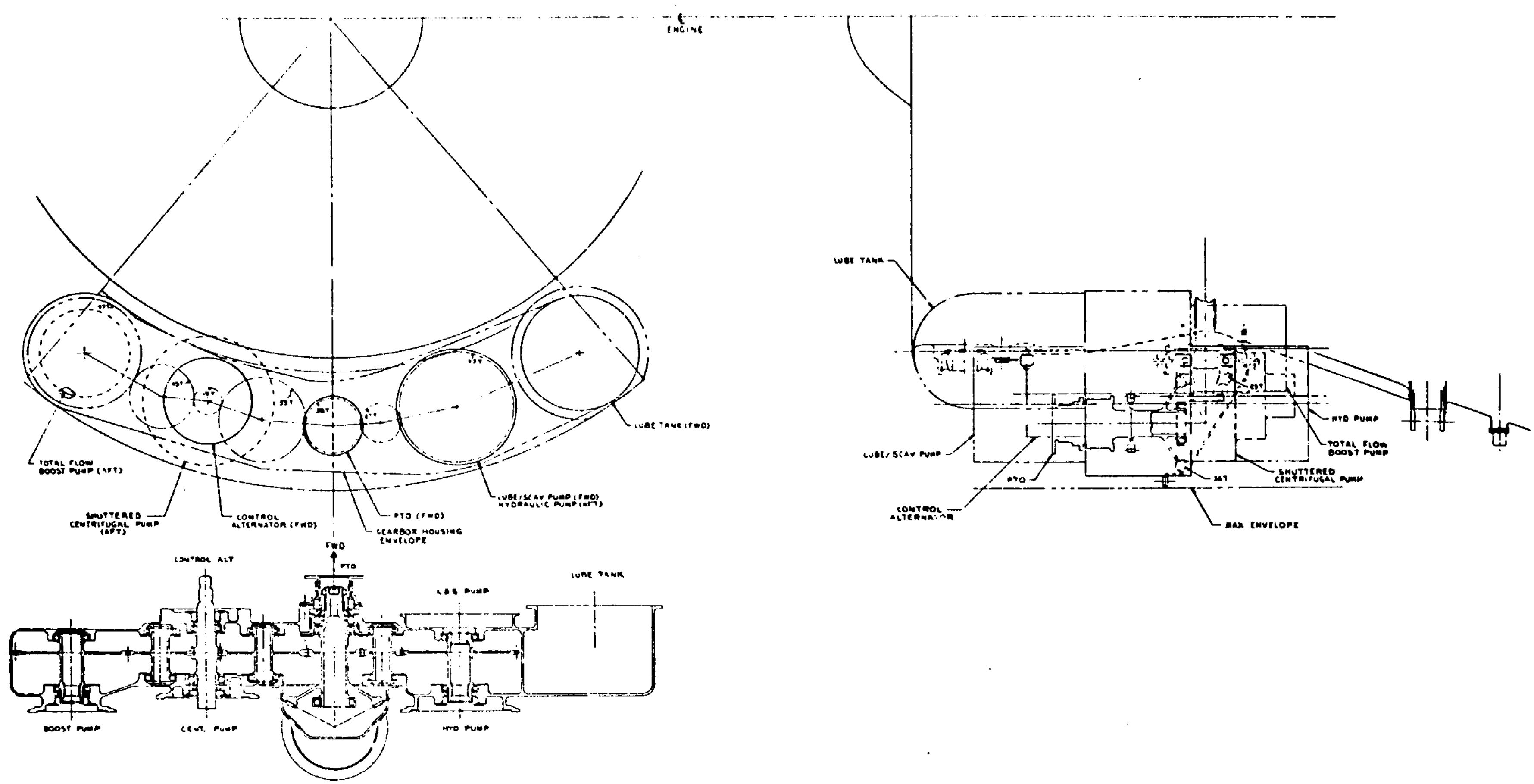



Figure 8. GE16/FLITE-1A Accessory Gearbox.

Fluid Power System

The GE16/FLITE-1A baseline fluid power system is shown in Figure 9. The fluid power system is utilized to actuate the variable fan duct ($A_{18}$) and exhaust ($A_9$) nozzles and consists of the following major components:

The engine electronic control provides the position schedules for the fan duct and exhaust nozzles. Linear variable differential transformers (LVDT) provide an electrical signal to the electronic control for position feedback.

The integral lube-hydraulic tank was selected primarily because of the weight saving and the reduction in envelope requirements over two separate reservoirs. This integration also offers some flexibility in that oil from one system can be utilized in the other system.

The unitized pump package consists of a centrifugal pump, a vane pump, and two high pressure servo pumps. This arrangement permits a weight saving and offers the simplification of driving four pumping elements from a common shaft. The centrifugal pump supplies the low pressure make-up and cooling flows for the vane pump and the high pressure output lines of the servo pumps. The centrifugal pump also supplies cooling flow to the low pressure lines in the two hydraulic systems. Fixed orifices in the shuttle valves provide cooling flow regulation from the low pressure centrifugal pump. The small vane pump has a positive displacement characteristic and provides the required pressure for position control to the two reversible high pressure servo pumps. The high pressure servo pumps produce minimum heat generation in the fan duct and exhaust nozzle position controls and were selected primarily for this reason. These pumps produce variable, bidirectional flows as a function of the electrical signal to the servo valves from the electronic control. The pumps produce only that flow and pressure required to position the load. During steady-state load conditions when the nozzles are fixed, the only heat losses are from the relatively small cooling flows and mechanical losses.

The rotary drive actuation is necessary for the exhaust nozzle system because of the long 22-inch stroke, the low load, and the 5 second actuation time requirements. These requirements have been satisfactorily met with the rotary drive system with a significant weight saving. A linear hydraulic actuation is utilized for the fan duct nozzle system because of the short 2.5 inch stroke, the high load, and the 2 second actuation time requirements.

The fuel/hydraulic heat exchanger is required during high hydraulic power utilization to remove the heat generated within the hydraulic system and thus maintain the hydraulic oil temperature within acceptable levels.

The fluid power system for the GE16/FLITE-1A is characterized by the fact that environmental heating tends to be the major contributing factor to the heat rejected to the fuel. The system was designed to minimize the environmental heating by judicious use of external insulation and by the determination

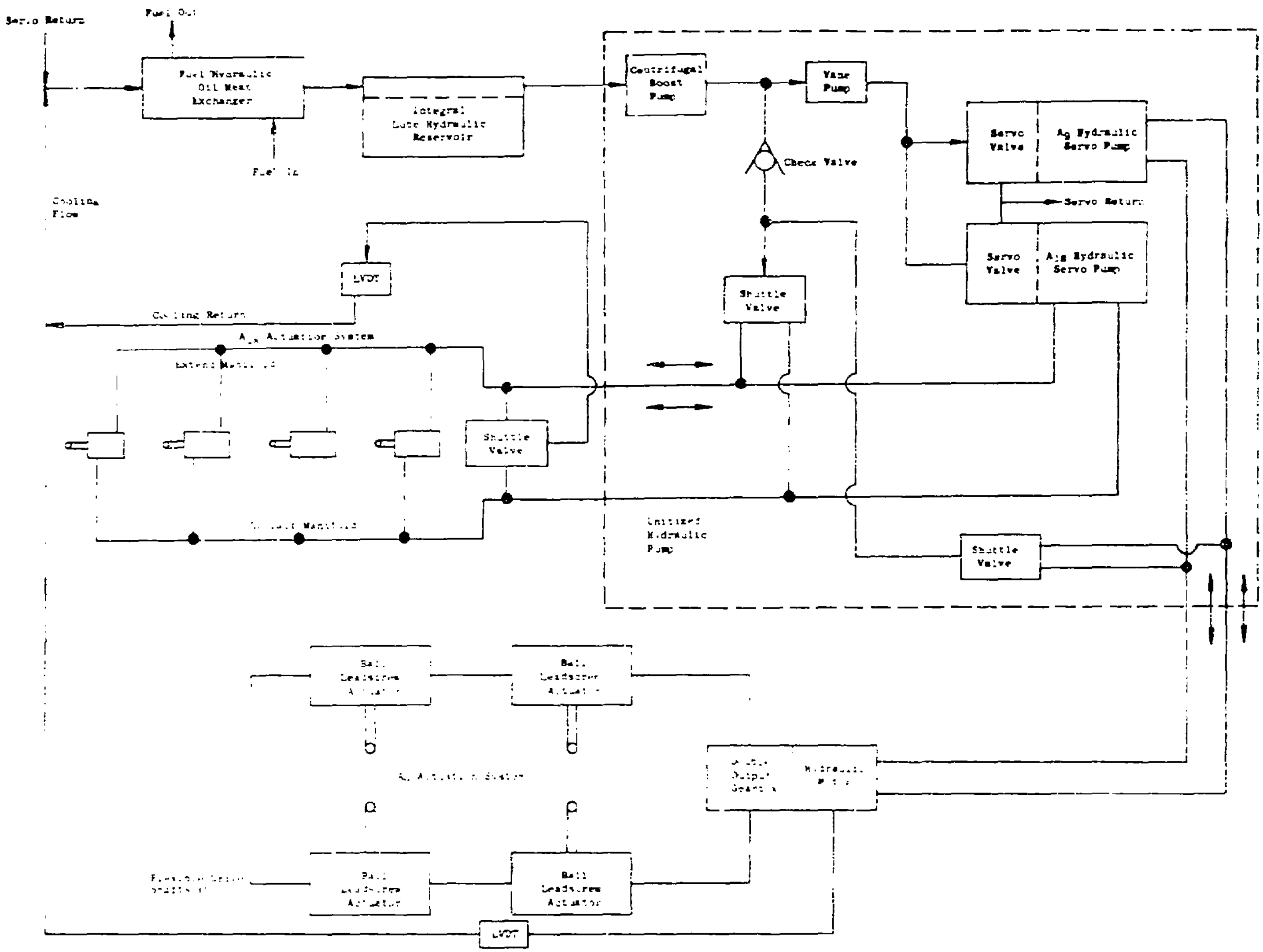



Figure 9. GE16/FLITE-1A Fluid Power System Schematic.

of the required cooling flows for steady-state operation to produce a low heat rejection system. The design point heat rejection for the GE16/FLITE-1A fluid power system is approximately 400 Btu/min, or about one-tenth of the levels produce in the lubrication system and by the main fuel pump. Thermal insulation is utilized on all fluid power system components and fluid lines exposed to the engine environment. For maximum altitude and Mach number the use of insulation results in approximately 50° F temperature rise from the discharge of the hydraulic pump through the lines and actuators and return lines to the hydraulic heat exchanger. This temperature rise is approximately one-tenth of the rise which would result with no insulation. In comparison, the integral hydraulic pump fluid temperature rise is approximately 33° F at this same flight condition. The weight of the insulation used in the fluid power system is about 4 pounds.

### B.2 Engine Performance

The estimated performance for the GE16/FLITE-1A engine was calculated with an electronic data processing deck. The performance is based on the following conditions:

- 1962 U.S. standard atmosphere
- MCAIR inlet ram recovery
- JP-5 fuel at 59° F with a fuel lower heating value of 18,500 Btu/lb
- Zero customer bleed air and horsepower extraction
- Variable area duct nozzle, fixed area core nozzle (internal performance only)

Pertinent sea level static take-off cycle characteristics of the engine are given in Table II.

Table II. GE16/FLITE-1A Engine Cycle Characteristics
100% Engine Sea Level Static Takeoff.

| | |
|---|---|
| Total Corrected Airflow | 277 pps |
| Fan Pressure Ratio | 2.33 |
| Overall Pressure Ratio | 11.95 |
| Bypass Ratio | 1.23 |
| Total Thrust (uninstalled) | 26,160 lb |
| Specific Fuel Consumption | 1.96 pph/lb |

### B.3 Thermal Analysis

The GE16/FLITE-1A fluid system schematic is shown in Figure 10. This system is composed of the fuel delivery system coupled through heat exchangers to the lubrication and fluid power systems. The design details of each of these three component systems have been discussed in paragraph B.1.

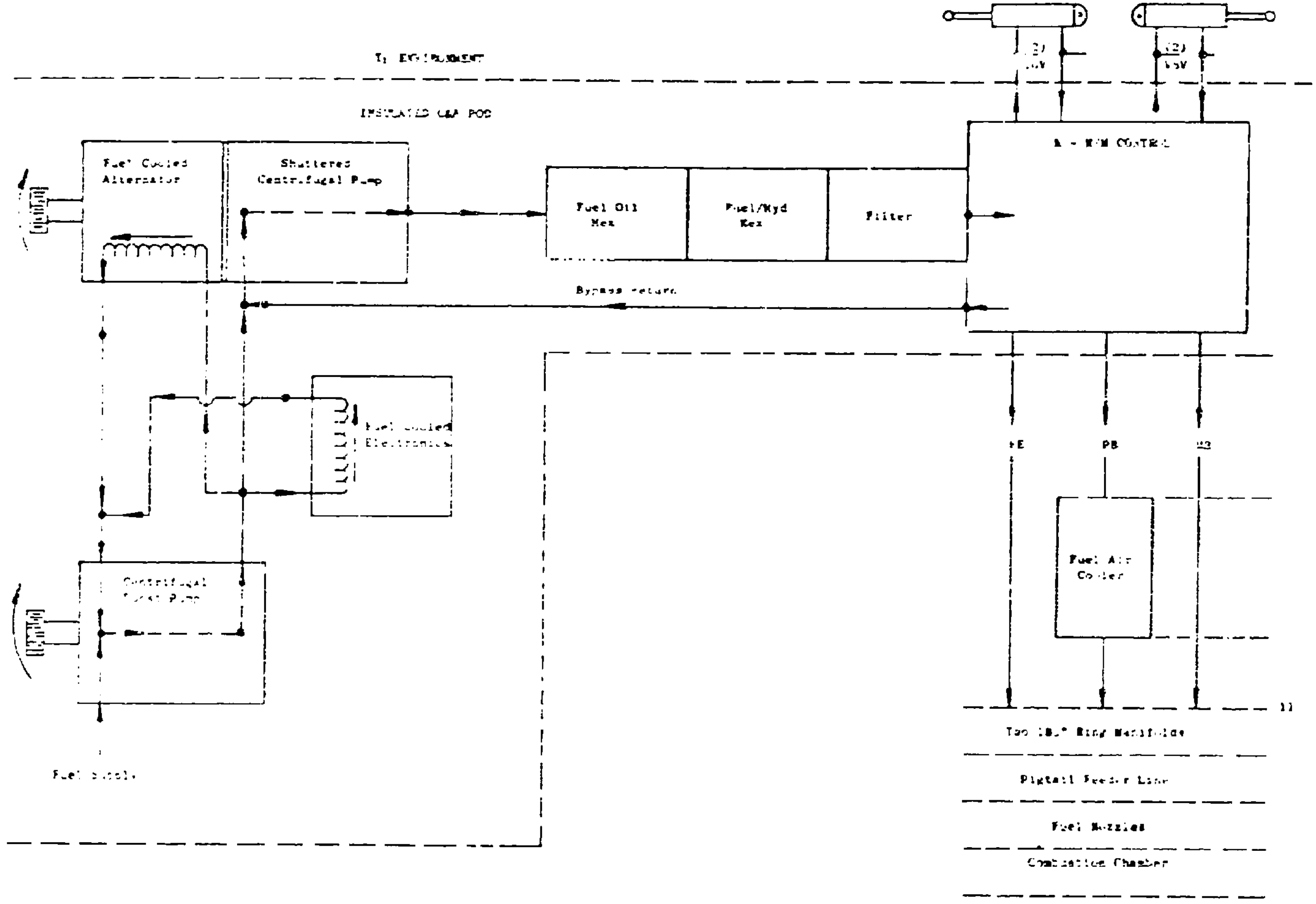



Figure 10. GE16/FLITE-1A Fluid System Schematic.

Since it was a purpose of this program to investigate the use of available heat sink, a prime objective was the creation of a mathematical heat balance model that accurately simulated on a digital computer the steady-state performance of the engine fluid system. This was accomplished with the GE16 thermal model, a computer program capable of analytically flying the mission for the baseline and subsequent Study 1, Study 2, and Study 3 engine designs.

Each of the heat producing elements of the engine fluid system was described in equation form. As the heat generation terms are functions of engine operating conditions, creating enthalpy balances for the fuel delivery, fluid power and lubrication systems necessitated simultaneous temperature dependent flow and pressure balances as well. All the fluid properties were assumed to be temperature dependent while the program output consisted of the complete fluid system temperature, pressure and flow profiles for a steady-state operating point.

Figure 11 shows the fluid system thermal profiles generated for the baseline engine during the mission. Indicated are the mission histories of the inlet fuel temperature, core nozzle fuel temperature, lubrication system supply and scavenge temperatures, and fluid power system supply and scavenge temperatures. The maximum permissible engine inlet fuel temperature of 200° F for the baseline configuration is reached during the idle-descent portion of the mission.

After the initial acceleration, the cruise-out phase occupies the next segment of the mission. The significant reduction in engine fuel flow from maximum to cruise power setting produces a sharp rise in the lubrication and fluid power system fluid temperatures. With the increasing altitude during cruise-out, the fuel flow decreases further, causing the gradual rise in the system temperatures shown in Figure 11. The application of maximum power during combat and turn produces momentary reductions in the fluid system operating temperatures, but with the beginning of return-cruise, the engine fuel flows again decrease and produce elevated temperature operation. It is during this portion of the mission that the shuttered centrifugal pump is beneficial. The change in slope of the fuel temperature profiles indicates the closing of the shutter, resulting in significantly lower power losses for the low fuel flows. The use of the shuttered device permits a reduction in the consumption of fuel heat sink during those portions of the mission where it is severely limited. At the end of the return-cruise mission phase, the lubrication and fluid power system supply temperatures reach their maximum permissible levels of 400° F. With the initiation of idle-descent and with no further compensating action taken, the nozzle fuel temperatures would reach about 450° F at the beginning of the descent and would remain over 325° F for four minutes. The lubrication and fluid power system supply temperatures would also rise to about a 580° F maximum during this time period. To prevent these overtemperature conditions, a fuel recirculation system was incorporated to increase the fuel flow during this critical mission phase. This system is regulated by the main fuel control and allows an additional 3,000 pph of fuel to be recirculated to the aircraft main feed tanks. With this system in operation, the end of the return-cruise portion of the mission becomes the point of maximum system temperature operation.

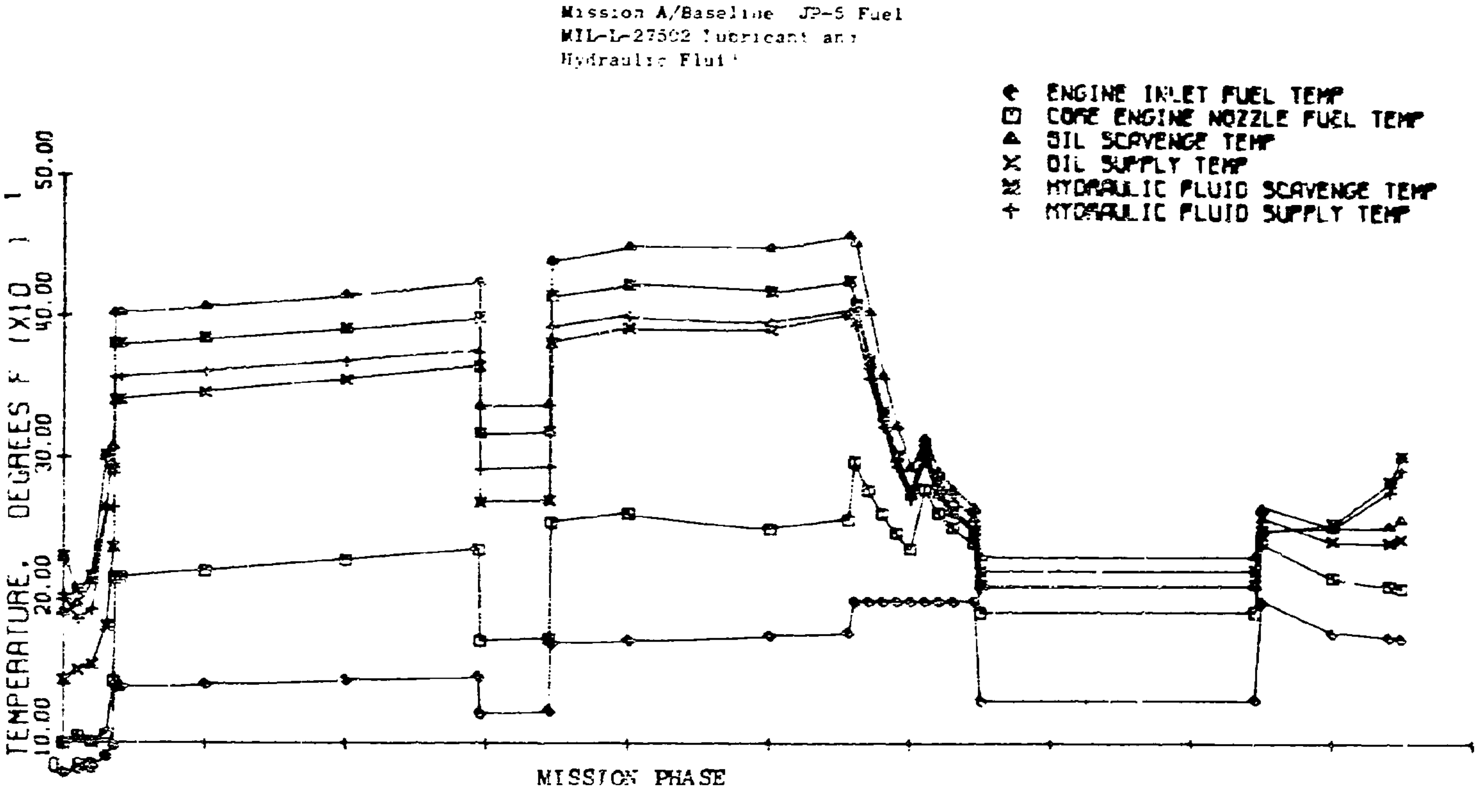



Figure 11. Mission A Baseline Fluid System Thermal Profiles.

## B.4 Interceptor Design Characteristics

The Mission A FLITE interceptors were designed to a technology level compatible with an anticipated initial operational capability (IOC) date of 1983. The primary design characteristics are presented in the following paragraphs.

This interceptor, illustrated in Figure 12 has a Mach 3+ cruise capability. The interceptor is in the 70,000 lb TOGW class with a wing area of 1,070 $ft^2$ and a fuel fraction of 0.50. The configuration is a two place (tandem) delta wing design with 75° swept leading edges and movable wing tips for lateral (roll) and longitudinal (pitch) control. Twin vertical surfaces provide the directions (yaw) control.

Propulsion is provided by the twin GE16/FLITE engines fed by two free-stream mounted, horizontal ramp, mixed compression inlets. Engine integration includes the sizing of an annular bypass plenum discharging bypass air aft during idle flight conditions at an angle of 15° with respect to the freestream airflow.

The aircraft structural concept consists of hot load carrying structure and the maximum use of metal and resin matrix composite materials projected compatible with a 1983 technology base.

Cabin and equipment environmental cooling is provided by a fuel augmented air cycle environmental control system. Thermal protection is provided in cockpit and equipment bay areas to limit internal temperatures.

The nose cross-sectional radius and radome fineness ratio have been determined by the requirements of a 36 inch, modified phased array AWG-9 radar. Aircraft armament is integrated in such a manner to preserve the fuselage fineness with a mix of eight long range and short range air intercept missiles carried internally on a rotating drum. Access for loading is provided from the underside while firing is accomplished out the top to avoid shock interference with the engine inlets.

## B.5 Weight Estimation Techniques

Structural weights are determined by conventional MCAIR estimation techniques; which include evaluation of the specific design and reference to statistical norms for component and material weights. Materials for the structural components are chosen to reflect current and projected material development effort compatible with IOC dates from the mid to late 1980's. Engine weights are based on engine weight scaling data provided by GE.

Weights for primary structure are based on application of a 3.5 g limit load factor at the basic flight design gross weight. Weight is allocated for the wing, a delta planform with rotating horizontal tips, twin vertical tails, and inlets using hot load carrying structure. Wing tip (control surfaces) weights are included with the basic wing. Weights for minimum gauge fuselage

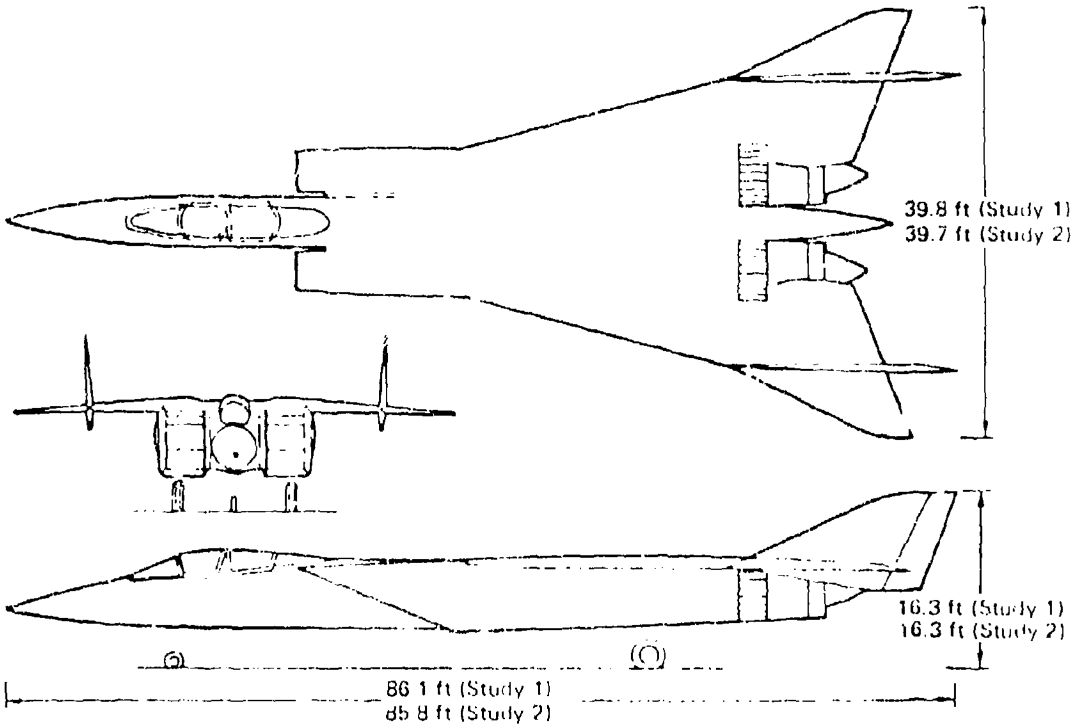



Figure 12. Mission A Aircraft.

covering and frames are designed for a 2,000 psf dynamic pressure environment. Longerons and stringers, including local supports to react the air loads, are weighed as a function of the fuselage bending moment, maximum depth, and body width. Fuselage weights also include the insulation required to protect selected compartment areas. Landing gear weight is based on the 2.0 g taxi load at maximum design gross weight. Air induction system weights are based on an ultimate duct pressure of 105 psi, and include insulation between the duct wall and fuel cell.

Metal and resin matrix composite materials are used where possible to provide maximum structural efficiency. This includes extensive application to the primary wing structure, tails, fuselage, and air induction groups.

B.6 Propulsion System Performance

The propulsion system for the Mission A vehicle consists of the GE16/FLITE duct burning turbofan and nozzle matched to a mixed compression inlet. Engine variations for the fuel and lubricant combinations investigated in the mission are presented in Section IV.

GE16/FLITE Engine and Nozzle - The GE16/FLITE-1A duct burning engine, illustrated in Figure 13 has a thrust rating of 26,160 lb, an airflow of 227 pps, a bypass ratio of 1.23, a cycle pressure ratio of 11.95, and a maximum turbine inlet temperature. Performance rating data for the reference engine are included in Figure 13. The scaling curves used to obtain the physical characteristics of an engine larger or smaller than the reference engine are presented in Figure 14.

The core consists of a multistage compressor driven by a single stage high pressure turbine. The low pressure spool consists of a two-stage fan and two-stage turbine, with the fan design incorporating variable inlet guide vanes. Reduced power can be obtained by either modulating the duct burner or the core engine fuel flow. The nozzle is a coannular convergent-divergent design with a fixed core throat area and a variable fan duct throat area. A cylindrical shroud is translated relative to the exhaust nozzle plug to provide the r[illegible]ired variation in fan duct exhaust expansion area ratio.

Air Ind[illegible] System Performance - The aircraft uses a two-dimensional mixed compres[illegible] inlet design with two horizontal external compression ramps. The first ext[illegible] compression ramp is set at fixed angle.

The second [illegible] is hinged relative to the first ramp, and is scheduled as a function of f[illegible]ght Mach number. The shock structure at the design point consists of two oblique shocks from the external ramps, a series of reflecting internal oblique shocks which form a shock train, and a terminal normal shock. The oblique shocks decelerate the airflow to a throat Mach number of 1.2. Downstream of the throat, the flow is expanded to a local Mach number of 1.35 where the terminal normal shock is located. The flow is then decelerated subsonically to the engine face. The length of the subsonic diffuser

Uninstalled Engine Characteristics

| | | |
|---|---|---|
| $F_{N_{max}}$ (SLS) | (lb) | 26,160 |
| $SFC_{max}$ (SLS | (lb/hr/lb) | 1.96 |
| Bypass Ratio (SLS) | | 1.23 |
| Airflow (SLS) | (lb/sec) | 277 |
| Weight* | (lb) | 3,200 |
| Length | (in.) | 130.8 |
| $D_{max}$ | (in.) | 58.8 |
| $D_2$ | (in.) | 42.0 |
| Program Variables | | |
| Fuel | | JP 5 |
| Fuel Interface Temperature | (°F) | 200 |
| Lubricant | | MIL-L-27502 |

*Includes nozzle engine/nozzle controls and accessories. Excludes airframe mounted accessories, accessory gear box and starter

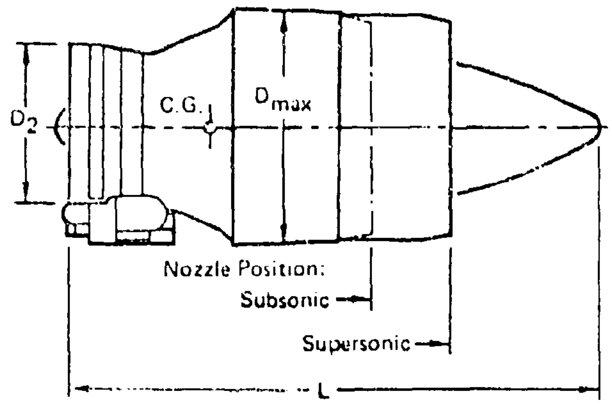



Figure 13. Engine Schematic, GE16/FLITE-1A.

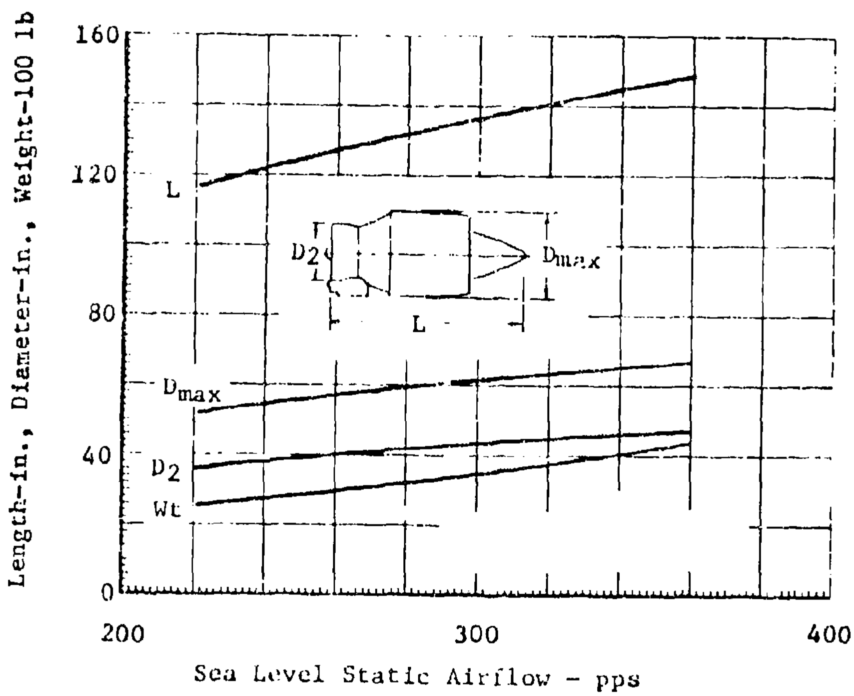



Figure 14. Scaling Characteristics, GE16/FLITE-1A.

lines joining the throat exit with the engine compressor face not exceed 9°. A bypass system is included in the design for inlet and engine airflow matching. The inlet operates in an external compression mode from Mach 0 to 1.8 and in a mixed compression (external and internal) mode from Mach 1.8 to design Mach number.

## B.7 Thermodynamic Characteristics

Design Temperatures - Maximum external surface temperatures were determined for the mission configuration to assist in the selection of airframe structural materials and determine thermal protection requirements. These temperatures, shown in Figure 15, represent the most severe thermal environments for the upper and lower surfaces.

The temperatures are based on aerodynamic heating effects using Spalding - Chiflat plate theory. Control surface deflections and shock wave induced interference heating are not considered.

Thermal Protection - Since the primary structure of the interceptor is designed to withstand the high temperature environment, numerous internal compartments require thermal protection via insulation. The insulation is sized to minimize the weight penalty based on a maximum sidewall temperature of 105° for the cockpit and a maximum internal temperature of 275° F for avionics compartments, wheel wells, and the missile bay. Insulation requirements for fuselage volume while limiting the fuel temperature rise to 20° F. Wing fuel tanks are provided sufficient insulation to prevent deposit formation resulting from breakdown of residual fuel. These thermal protection provisions are accounted for in the weight estimations presented earlier.

Airframe Heat Loads - Airframe heat loads which are absorbed by the fuel before delivery to the engines are summarized in Table III as a function of mission phase. Hydraulic and electrical system heat loads are based on system power provisions ranging from 70 to 272 horsepower. Hydraulic heat loads include heat generated due to pump inefficiencies and environmental heating of actuators and lines. Heat loads resulting from generation of electrical power are assumed to be constant throughout the mission. Boost pump heat rejection to the fuel (both delivered fuel and stored fuel) is based on pump duty cycles which minimize fuel heating. The ECS heat rejection to the fuel results from the use of fuel to augment ram air as a heat sink for the ECS.

Environmental Control System - The Mission A bootstrap air cycle ECS, shown in Figure 16 uses engine bleed air for cockpit pressurization and avionics cooling. This system, which is similar to those installed in existing aircraft, is modified for the mission application to include a fuel-to-air heat exchanger located upstream of the ECS refrigerationpackage turbine and a boost compressor upstream of the primary heat exchanger. Use of fuel to augment ram air as a heat sink reduces ECS turbine inlet temperatures thereby reducing turbomachinery work requirements, and also ram air system induced aircraft penalties. When engine fuel demands are small (such as during descent),

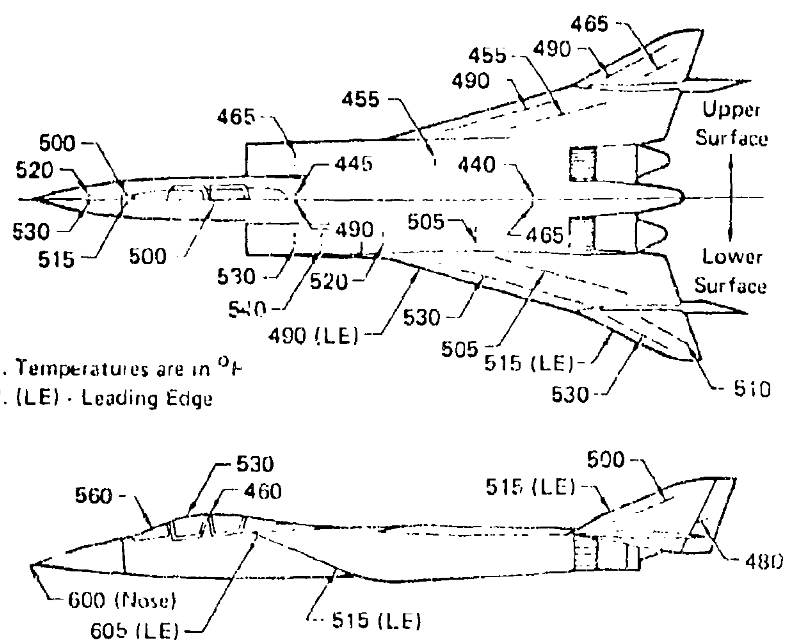



Figure 15. Maximum Surface Temperature, Mission A.

Table III. Mission A Interceptor Summary of Heat Loads to Fuel.

| | Heat Load (Btu/min) | | | |
|---|---|---|---|---|
| Mission Phase | Environmental Control System | Hydraulic System | Electrical System | Boost Pumps |
| Takeoff | 0 | 2,380 | 470 | 134 (a) |
| Start of Cruise | 11,400 | 2,860 | 470 | 86 (a) |
| Combat | 11,400 | 3,045 | 470 | 67 (a) |
| End of Cruise | 11,400 | 3,230 | 470 | 93 (a) |
| Descent to 40K ft | | | | |
| (a) After 1 min | 7,500 | 3,126 | 470 | 46 (b) |
| (b) After 2 min | 4,400 | 3,022 | 470 | 48 (b) |
| (c) After 3 min | 2,600 | 2,918 | 470 | 53 (b) |
| (d) After 4 min | 1,300 | 2,814 | 470 | 55 (b) |
| (e) After 5 min | 0 | 2,710 | 470 | 57 (b) |
| Loiter at 40K ft | 0 | 2,380 | 470 | 101 (c) |
| Descent to S.L. | 0 | 2,380 | 470 | 65 (b) |

(a) To delivered fuel.

(b) Small fraction to delivered fuel, remainder to tank.

(c) Small fraction to delivered fuel, remainder lost to environment.

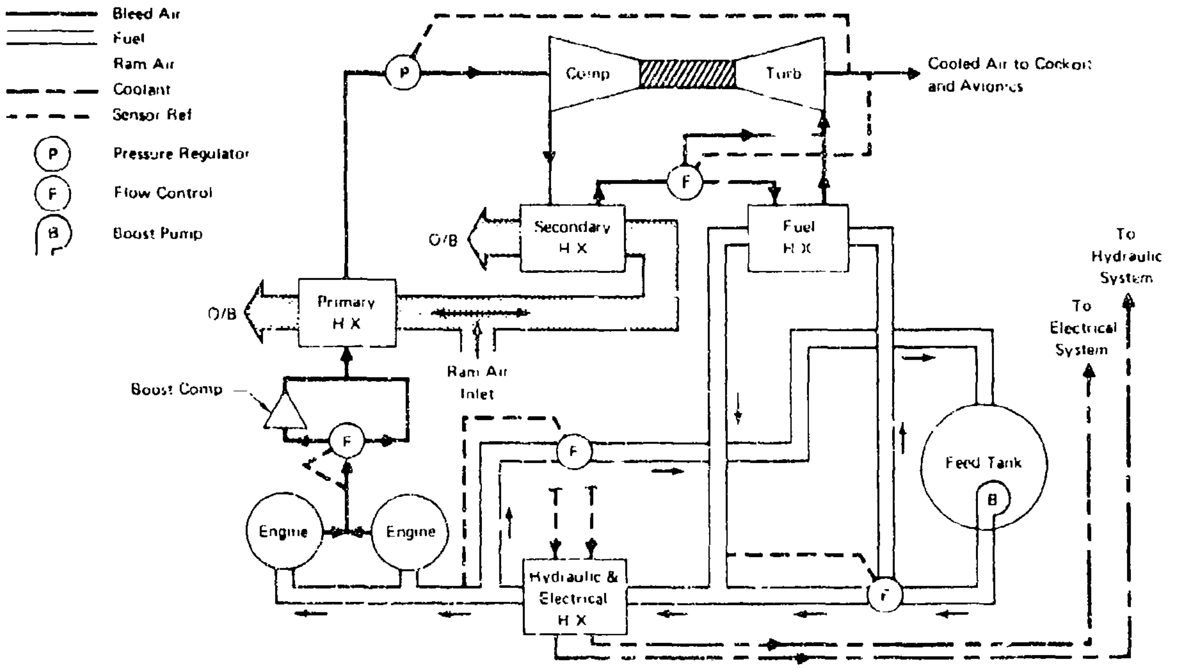



Figure 16. Mission A Interceptor ECS Schematic.

it is necessary to circulate excess fuel to absorb the airframe heat loads to remain below the maximum allowable engine/airframe fuel interface temperature. The boost compressor is included to supplement engine bleed pressure during mission phases (such as descent) where available pressure is not adequate to provide acceptable environmental pressurization.

## C. MISSION B BASELINE

### C.1 Engine Design

#### General Description

The powerplant for the Mission B baseline interceptor is the GE14/FLITE-2A engine. This engine is a variable cycle turboramjet and represents an advanced engine incorporating technology of the late 1980 time period.

#### Fuel Delivery System

The GE14/FLITE-2A baseline fluid system schematic is shown in Figure 17. The system consists of the fuel delivery system coupled through the fuel/oil and fuel/hydraulic heat exchangers to the lubrication and fluid power systems, respectively.

The fuel delivery system receives fuel from the aircraft fuel tank boost pumps at between 15 and 40 psia depending upon altitude. The engine fuel pumps increase the fuel pressure sufficiently to overcome all system pressure losses and inject fuel into the engine combustors.

The electronic control provides the schedules for the metered fuel flow to the three burner systems. This control transmits a position signal to the torque motors in the main fuel control to position the fuel metering valves. Linear variable-differential transformers, located in the fuel control provide the feedback position to the electronic control. The fuel flow schedules to the core engine combustor, the ram-duct pre-burner and the ram-duct main burner are functions of altitude and Mach number.

Thermal analysis of the fluid systems over Mission B shows that the critical phase for fuel heat sink utilization is during the ramjet idle-descent. During this mission phase, recirculation to the aircraft main feed tank is utilized to maintain system fluid temperatures within acceptable limits. The recirculation system for the GE14/FLITE-2A engine is similar to the system used for the GE16/FLITE-1A engine. An additional control function is provided in the main fuel control which reroutes a specific amount of the total inlet fuel flow to the aircraft main feed tank at the beginning of the ramjet idle-descent. The initiation of the recirculation fuel flow is a function of throttle angle and fuel temperature level at the engine fuel control. At idle throttle angle positions and when the fuel temperature reaches approximately 300° F, the recirculation system is activated and a portion of the inlet fuel flow is routed through a fixed orifice in the engine fuel control to the aircraft fuel tanks.

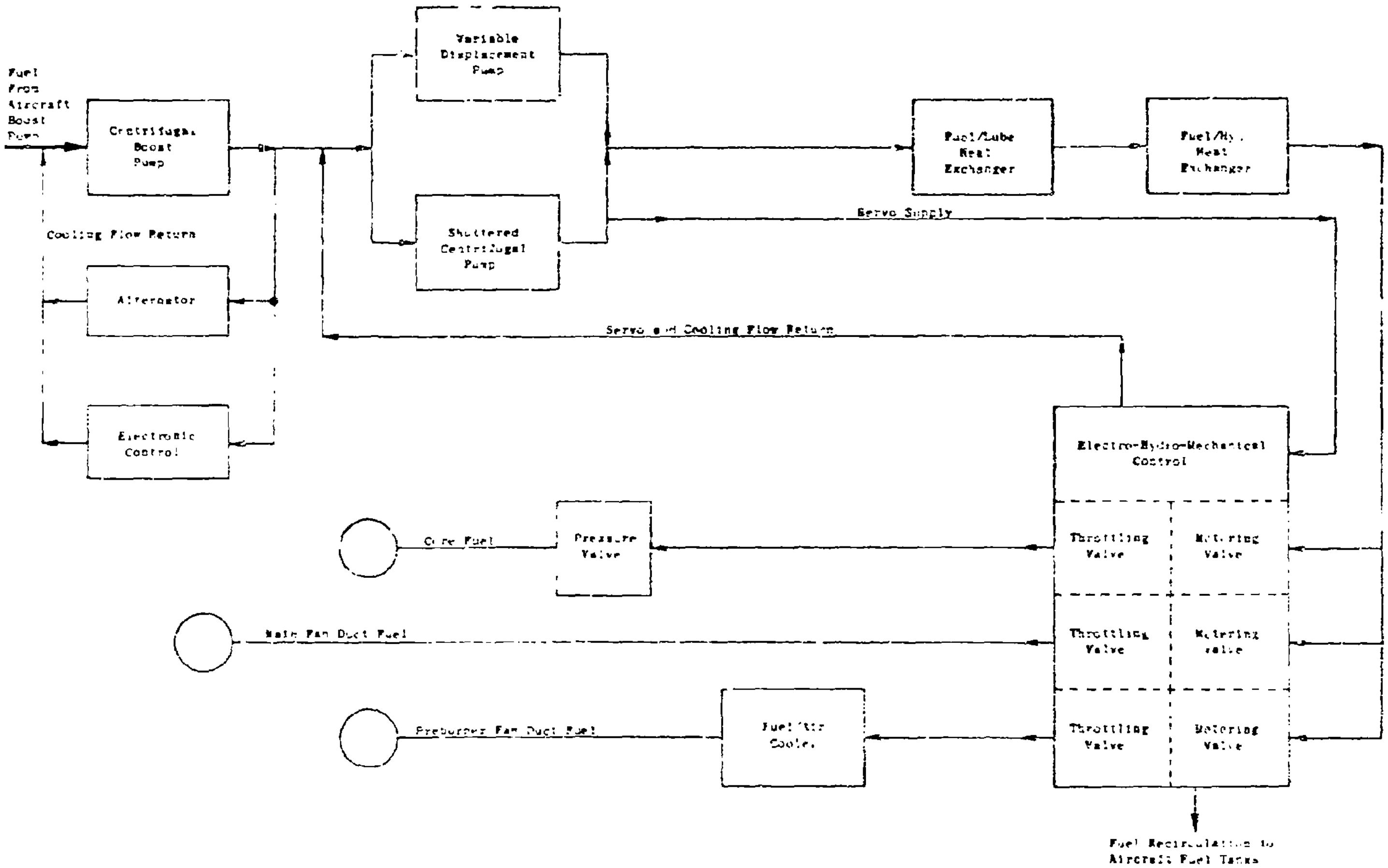



Figure 17. CS14/FLITE-2A Fuel Delivery System Schematic.

The engine fuel is the major source of heat sink for cooling engine and aircraft components. In the engine fluid system, the fuel is used to cool the control alternator, electronic computer, boost pump and main fuel pumps. In addition, the fuel absorbs the heat generated in the lubrication and fluid power systems, the heat flow from the environment, and cools the sump pressurization and cooling air. With the many demands upon the fuel heat sink and its marginal capacity during portions of the mission, it was important that the fuel delivery system components be selected with minimum heat generation being the primary concern.

In addition to its low thermal input to the fuel, the throttling type fuel control was selected because of its high efficiency. During engine starting and acceleration to idle, the control utilizes fuel flow from the variable displacement vane pump. A pressurizing valve in the core engine supply is required during these low flow conditions to provide adequate back pressure for the fuel control servo functions. For high fuel flow conditions, the fuel control system operates by throttling the flow and maintaining a fixed back pressure on the centrifugal pump.

The engine fuel delivery pump package consists of a total flow centrifugal boost pump, a variable displacement vane pump and a shuttered centrifugal pump. The boost pump provides small size and weight and proven reliability. This low speed centrifugal pump can operate at low input pressures from the aircraft boost pump without cavitation, and is capable of supplying sufficient pressure to prevent cavitation in the high pressure pumps. The variable displacement vane pump exhibits overall high efficiency over its flow range. This pump is always in operation, being the sole source of supply to the core engine during startup and acceleration to idle and participating with the other pumps to supply fuel to the engine during other flight conditions. During certain operating conditions when the engine is at flight idle power setting, the total fuel flow can be provided by the variable displacement vane pump. This allows this high efficiency pump to be utilized during low fuel flow conditions when heat sink requirements are critical. Since the primary user of the fuel heat sink in the fuel delivery system is the high flow main fuel pump, utilization of the shuttered centrifugal pump design prevents excessive thermal stressing of the fuel during the cruise portions of the mission. Closing of the shutter at reduced fuel flows prevents recirculation in the pump and significantly reduces the power losses. By closing the shutter at the flow rates below approximately 10 percent of the maximum fuel flow, the pump power loss is reduced by about 50 percent.

Thermal insulation is utilized on all fuel delivery system fluid lines exposed to the engine environment. The insulation was selected to provide for the maximum temperature reduction consistent with the location of the fluid line in the environment and the insulation characteristics.

Lubrication System

The baseline lubrication system schematic for the GE14/FLITE-2A engine is shown in Figure 18 and the associated sump area layout is presented in Figure 19.

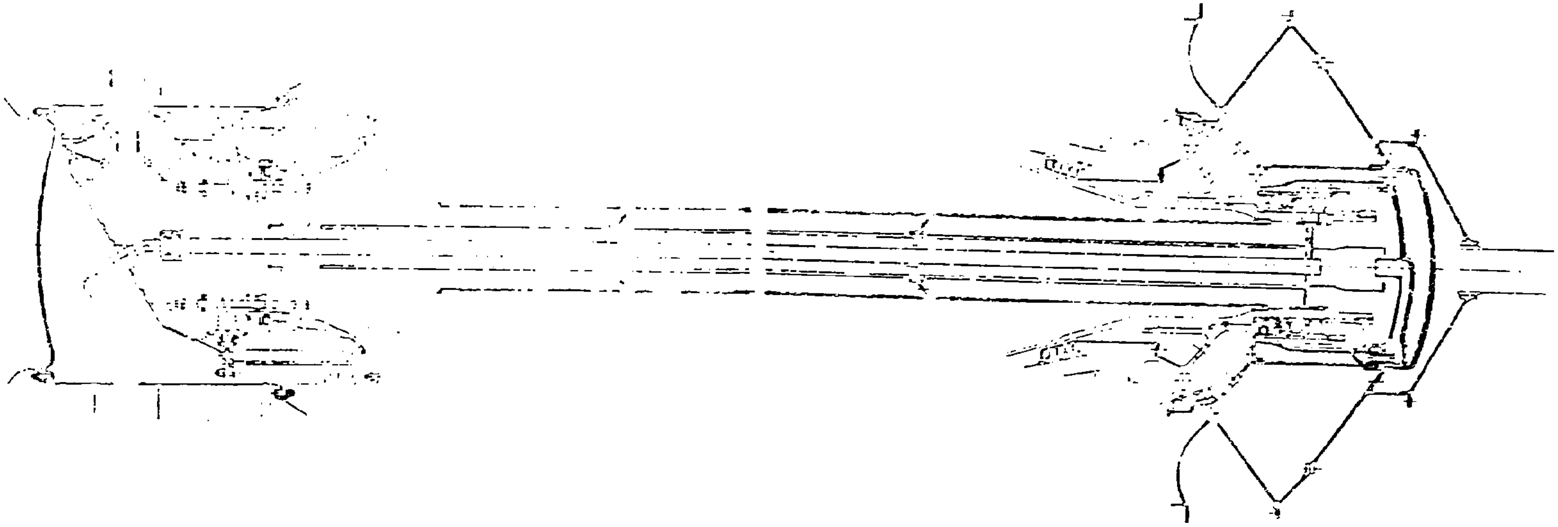


Figure 1

GE... FLITE-23 Oil Sump Layout Drawing.

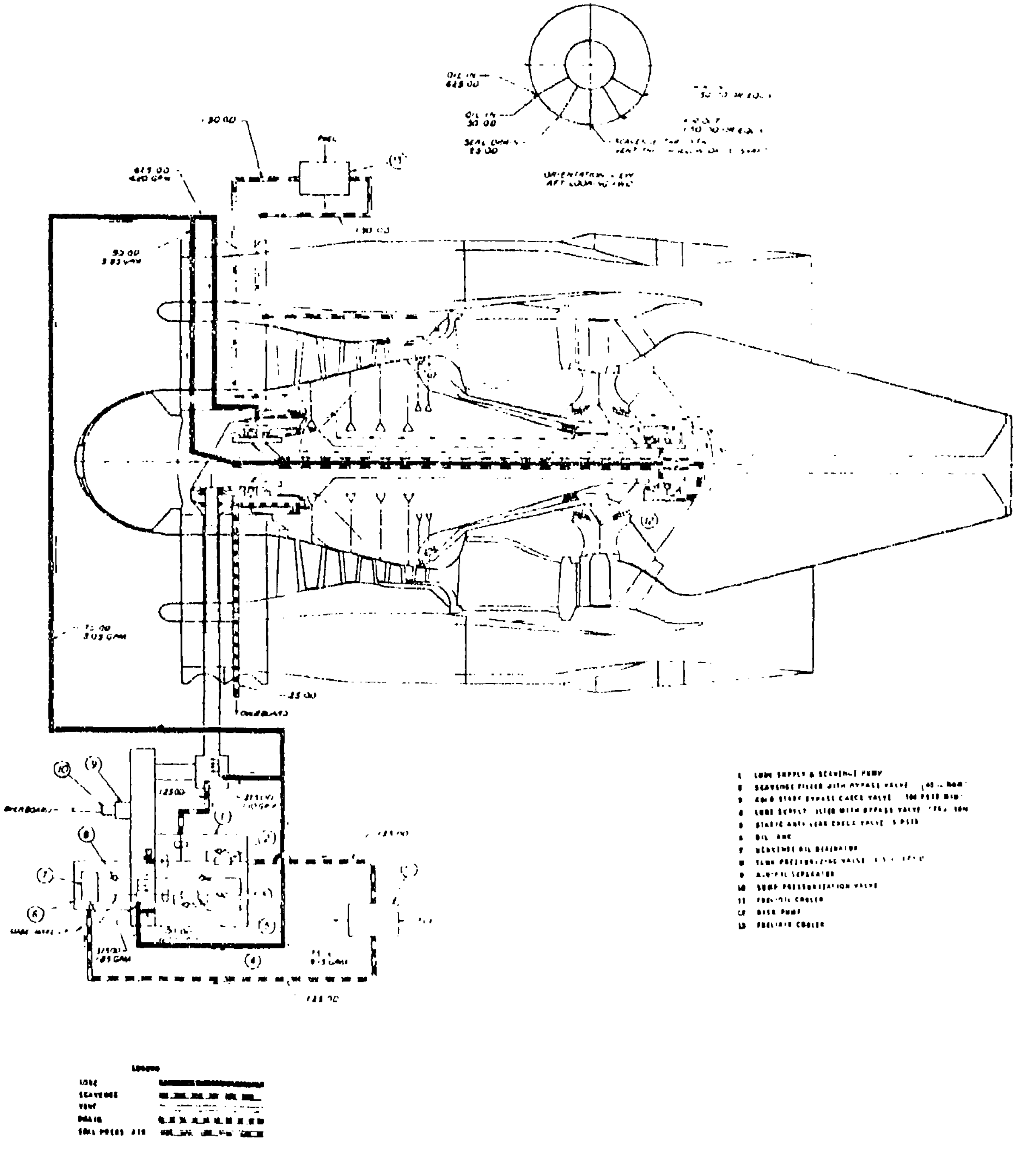


**Figure 19. GE'4/FLITE-2A Lubrication System Schematic.**

Oil is supplied to the inlet of the supply element by gravity feed from the oil tank. Oil under pressure is then supplied by the pump to the supply filter, which serves to protect the oil jets from contamination. This filter is equipped with a pressure relief valve which opens at a predetermined pressure differential and allows full oil flow to continue to be supplied to the engine should the filter become plugged. Oil supply pressure is limited during cold starts by another pressure relief valve which bypasses some oil directly to the gearbox if the supply pressure exceeds a maximum level. At all pressures less than this limiting value, the entire output from the filter is directed to the oil supply system. A static antileak check valve is provided to limit leakage from the tank to the engine to an acceptable level during engine shutdown. Oil is supplied to three areas of the engine; the accessory gearbox, the "A" sump/inlet gearbox combination, and the "B" sump. The "A" sump is supplied through a strut in the front frame which connects to a rotating oil supply pipe inside the shaft. A carbon seal is used to seal between the stationary frame and the rotating shaft. Leakage from this oil seal is contained by the "A" sump. The oil supply distribution for the baseline engine is given in Table IV.

The "B" sump is scavenged by a disk pump driven by the core engine. This pump has a tangential collector in the stationary sump wall to recover the velocity head. The scavenge oil is then piped inward to the engine centerline and discharged into a rotating scavenge tube which pumps the oil forward to the "A" sump by centrifugal force. During the ramjet mode of operation when the core engine is windmilling at less than 10 percent speed, the gearbox-mounted accessories including the lubricant supply and scavenge pump are driven by a ram air turbine. The "B" sump scavenge oil is used to cool the No. 1 bearing inner race before being discharged into the "A" sump. This oil is not used to lubricate the bearing. The "A" sump/inlet gearbox area is scavenged by gravity through the PTO shaft housing to the accessory gearbox. The accessory gearbox is scavenged by a single scavenge pump element, and the oil is then directed to the scavenge filter. The scavenge filter contains a bypass valve which allows the oil to bypass the filter element in the event it becomes plugged by contamination. From the filter, the oil is piped to the fuel/oil heat exchanger where the heat from the engine is transferred to the fuel. From the heat exchanger, the oil is returned to the tank.

Pressurization air is extracted from the compressor at the second stage stator exit tip. This air is first cooled in a fuel/air heat exchanger and then piped to the No. 1 seal pressurization cavity through a strut in the front frame. A portion of this air flows aft inside the main shaft and around the rotating scavenge tube to the No. 2 seal pressurization cavity. In addition to its primary function of pressurizing these seals, this air is used to isolate the sump walls and the rotating scavenge tube from hot cycle air.

Vent air from the "B" sump flows to the "A" sump through the rotating scavenge tube. The "A" sump is then vented to the accessory gearbox through the hollow PTO shaft. The oil tank is also vented to the gearbox. The vent line from the oil tank contains a tank pressurization valve which maintains the tank pressure above sump vent pressure. The increased tank pressure is

Table IV. GE14/F[illegible]TE-2A Lubrication System
Design Oil Flow Distribution

| Component | | Design Flow (gpm) |
|---|---|---|
| "A" Sump | | 3.50 |
| "B" Sump | | 3.85 |
| Inlet Gearbox | | 0.70 |
| Transfer Gearbox | | 1.10 |
| Accessory Gearbox | | 1.85 |
| | Total Supply | 11.00 |
| Transfer Gearbox Scavenge Capacity | | 20.10 |
| Accessory Gearbox Scavenge Capacity | | 4.05 |
| | Total Scavenge | 24.15 |

provided to pressurize the supply pump inlet and to reduce the variation in oil supply quantity to the engine under varying flight conditions. The air flow through th's valve is sufficient to maintain tank pressure at altitude. All of the air delivered to the accessory gearbox is vented overboard through an air/oil separator and a sump pressurization valve. A dynamic air/oil separator is used, being driven through the gearbox. The sump pressurization valve assures adequate pressure in the sumps for scavenging at altitude.

Fluid Power System

The GE14/FLITE-2A baseline fluid power system is shown in Figure 20. The fluid power system is utilized to actuate the core exhaust nozzle ($A_8$), the outer ram duct exhaust nozzle ($A_9$), the ramjet exhaust nozzles ($A_{18}$) and to position the turbine nozzle variable vanes ($A_4$), the variable stator, vanes (VSV) and the ram pre-burner swirl cups ($A_{25}$). The position schedule for the variable nozzles, vanes, and swirl cups are provided by the engine electronic control. Linear variable differential transformers (LVDT) provide electrical signals to the electronic control for position feedback.

The separate hydraulic tank was selected primarily because of the requirement for supplying fluid for six separate actuation systems exposed to high temperature environments. The tank is pressurized to approximately 30 psia and contains a fluid deaerator.

The centrifugal boost pump was selected because of size, weight, and reliable operating experience. A prime function of this total flow centrifugal pump is to prevent cavitation in the high pressure hydraulic pumps.

The pressure compensated pump provides the capability to power the $A_4$, $A_{25}$, $A_{28}$, and VSV actuation systems from a single pump. This constant pressure variable displacement pump supplies a maximum flow of 19 gpm for maximum actuation requirements and is throttled to a 6 gpm output for steady-state operation. The low pressure and steady-state cooling flow requirements of 6 gpm minimizes power losses under steady-state operating conditions.

The four servovalves used for $A_4$, $A_{25}$, $A_{28}$, and VSV fluid flow control are necessary because of the requirement to control the flow to the separate systems upon a demand signal from the electronic control. The servo control valves are designed to minimize heat loss due to the required throttling effects.

The high pressure servopumps were selected for the $A_8$ and $A_9$ exhaust nozzle position controls because of the high nozzle loads encountered at the high Mach number side of the flight envelope. The pumps produce variable, bidirectional flows as a function of the electrical signal to the servovalves from the electronic control. The pumps produce only that flow and pressure required to position the load. During steady-state load conditions when the nozzles are fixed, the heat losses are from the pump and the engine environmental heat input to the fluid lines and components.

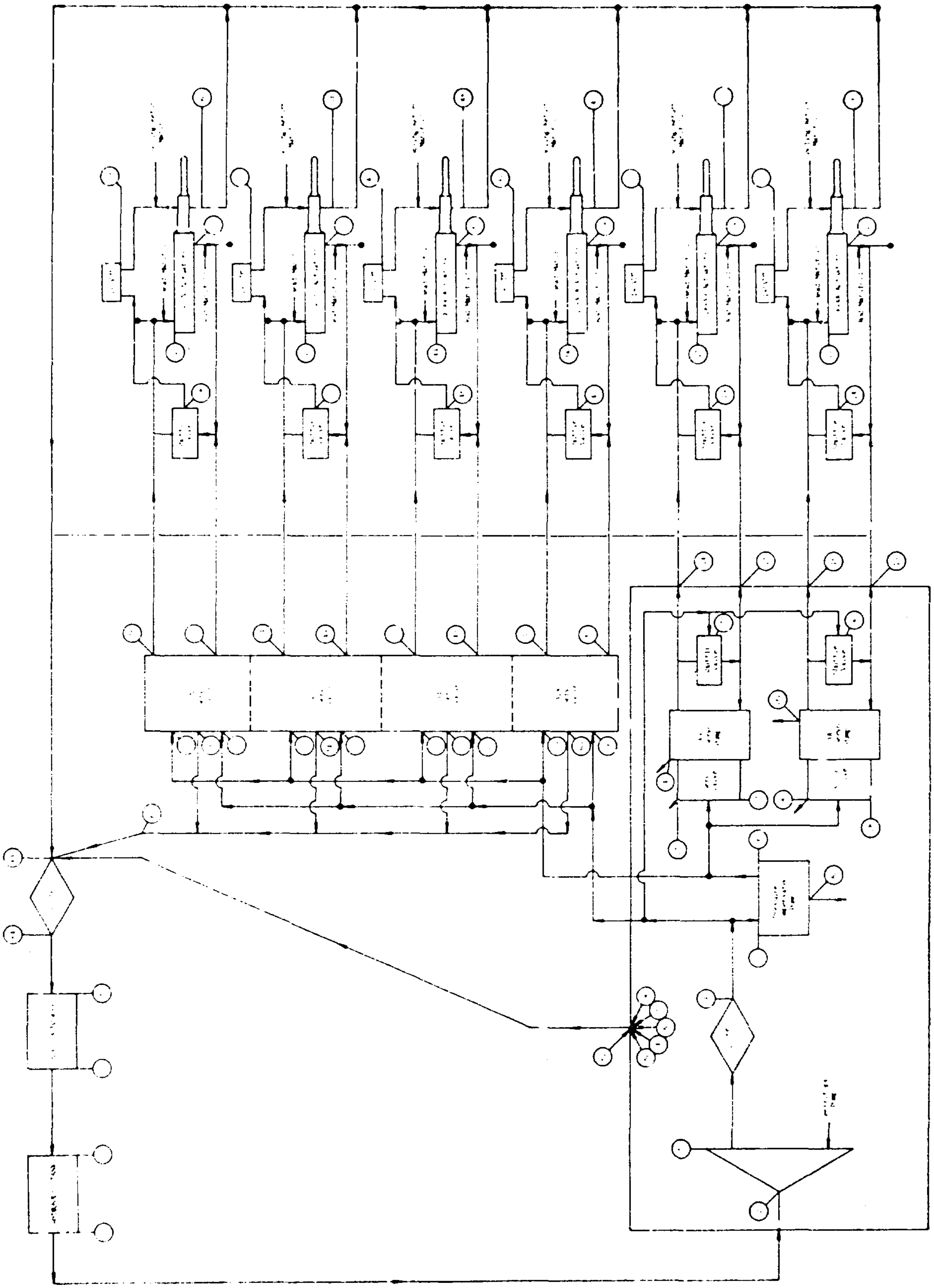


Figure 20. GE14/FLITE-2A Fluid Power System Schematic.

Linear hydraulic actuators are used for all of the actuation systems because of very short stroke requirements and limited space available in the engine envelope. Because of the high load requirements of the $A_8$ and $A_9$ actuation systems, two-stage hydraulic actuators are used.

Hydraulic fluid is supplied from the pressurized hydraulic tank to the centrifugal boost pump. This pump then supplies flow to the servopumps, to the pressure compensated pump, and to the actuators for cooling. The servopumps power the $A_8$ and $A_9$ actuators and the pressure compensated pump powers the $A_4$, $A_{18}$, $A_{25}$ and VSV actuators. The pressure compensated pump also provides servo control flow to the $A_8$ and $A_9$ servopumps.

Actuator cooling flow is provided in both the high and low pressure sides of the actuation systems. The high pressure side is cooled with a cross-piston cooling flow. This high pressure also positions the shuttle valve in the supply manifolds to allow a cooling flow from the centrifugal pump to flow into the low pressure sides of each actuation system. The total cooling flow from each system is routed through a shuttle valve to an LVDT and is returned to the tank via the fuel/hydraulic heat exchanger.

The GE14/FLITE-2A fluid power system was designed to minimize the heat addition which occurs in the pumps because of high pressures and pump inefficiencies and in the fluid lines and actuators due to the exposure to high ambient temperature environments. Environmental heating tends to be the major contributing factor to the heat rejected to the fuel. The system was designed to minimize the environmental heating by judicious use of external insulation and by the determination of the required cooling flows for steady-state operation to produce a low heat rejection system. Thermal insulation is utilized on all fluid power system components and fluid lines exposed to the engine environment. For maximum altitude and Mach number, this insulation reduces the temperature rise in the lines and actuators caused by environmental heating to approximately 40° F. The design point heat rejection for the GE14/FLITE-2A fluid power system is approximately 2,680 Btu/min.

C.2 Engine Performance

Estimated performance for the GE14/FLITE-2A engine was calculated with the Electronic Data Processing cycle deck. Engine performance is based on JP-5 fuel having a heating value of 18,500 Btu/lb and at a temperature of 59° F (enthalpy of 184.3 Btu/lb).

C.3 Thermal Analysis

The GE14/FLITE-2A fluid system schematic is shown in Figure 21. As discussed in paragraph C.1, this system is composed of the fuel delivery system coupled through the fuel/oil and fuel/hydraulic heat exchangers to the lubrication and fluid power systems, respectively.

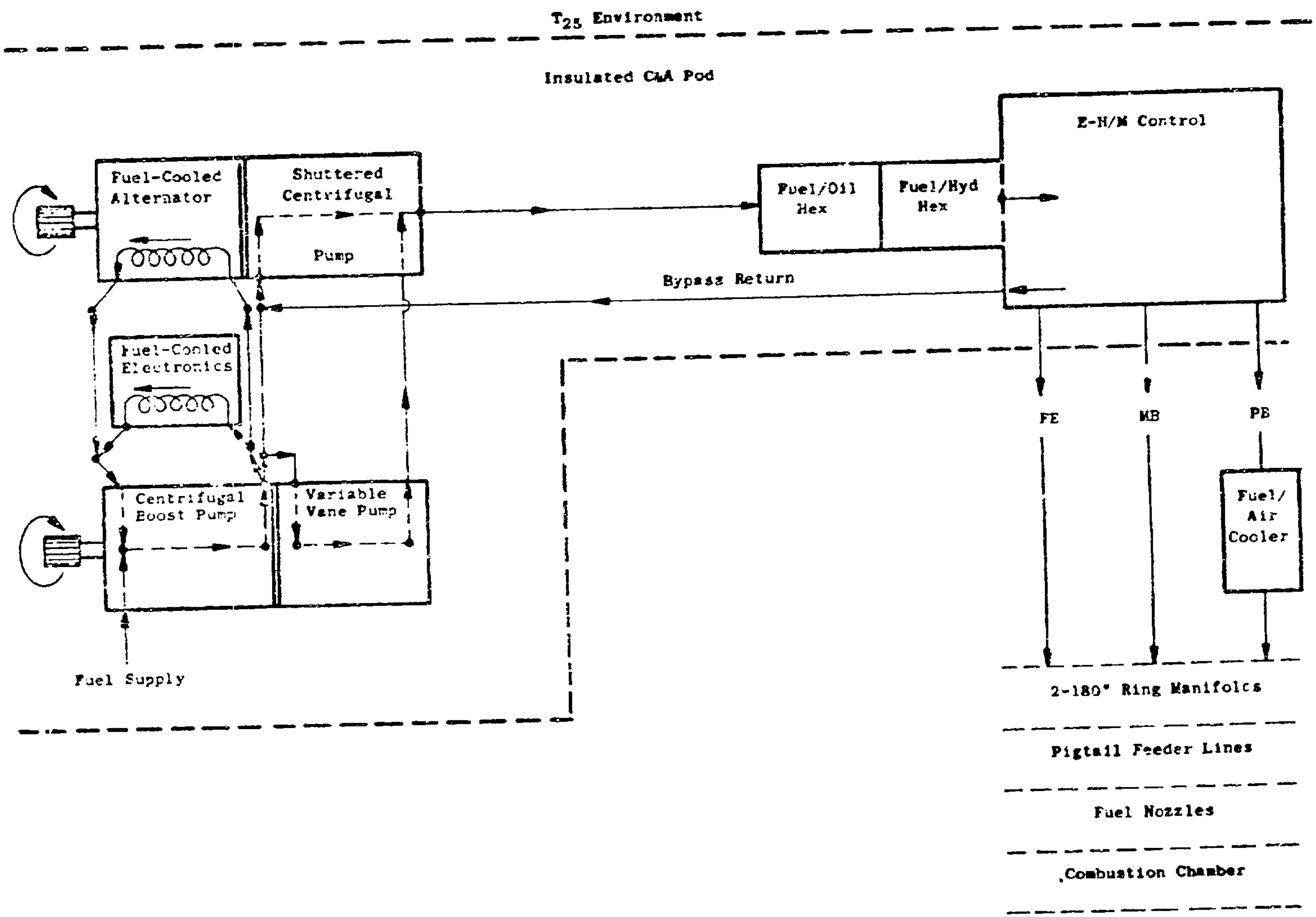



Figure 21. GE14/FLITE-2A Fluid System Schematic.

The performance of the GE14/FLITE-2A engine fluid system was mathematically simulated by the creation of a digital computer model. This computer program provided the capability of analytically flying Mission B for the baseline and the subsequent four study engine designs and determining the engine system performance for steady-state operating points. This model was the principal tool used to identify and investigate the uses of the fuel heat sink for Mission B.

In the development of the computer model, each of the heat producing elements of the engine fluid system was described in equation form. These heat generation terms were described as functions of the engine operating conditions. Since the fuel, lubricant, and hydraulic fluid properties were assumed to be temperature dependent, the establishing of enthalpy balances for each component system required simultaneous flow and pressure balances. This complex iterative process was accomplished through the use of a modified Newton-Raphson numerical technique for the solution of sets of nonlinear ordinary differential equations.

Figure 22 shows engine fluid system temperature profiles generated during the Mission B baseline. Indicated in the plot are the following eight system variables.

- o Engine inlet fuel temperature
- o core nozzle fuel temperature
- o ram pre-burner nozzle fuel temperature
- o ram main burner nozzle fuel temperature
- o lubrication system supply temperature
- o lubrication system scavenge temperature
- o fluid power system supply temperature
- o fluid power system scavenge temperature

The maximum permissible engine inlet fuel temperature of 200° F (JP-5) for the baseline configuration is reached during the final idle-descent portion of the mission.

As with Mission A, the significant reductions in engine fuel flow for the cruise power setting produce sharp rises in system temperatures as the transitions are made from maximum power setting. At the end of the cruise-out mission leg, the fluid power system reaches its point of maximum temperature operation while the lubrication system does not experience its maximum temperature condition until the end of return cruise.

With the complex modes of operation for the GE14/FLITE-2A engine and the high flight speeds, temperature dependent manifold cooling flows are necessary to cool the burner fuel lines and minifolds when the respective burners are not in operation. Although the main engine control is further complicated by the additional logic and hardware to provide this function, the cooling flows are an effective means of maintaining the fuel in the burner lines to within the design JP-5 unlimited service thermal stability limit of 325° F when the respective burners are not in operation.

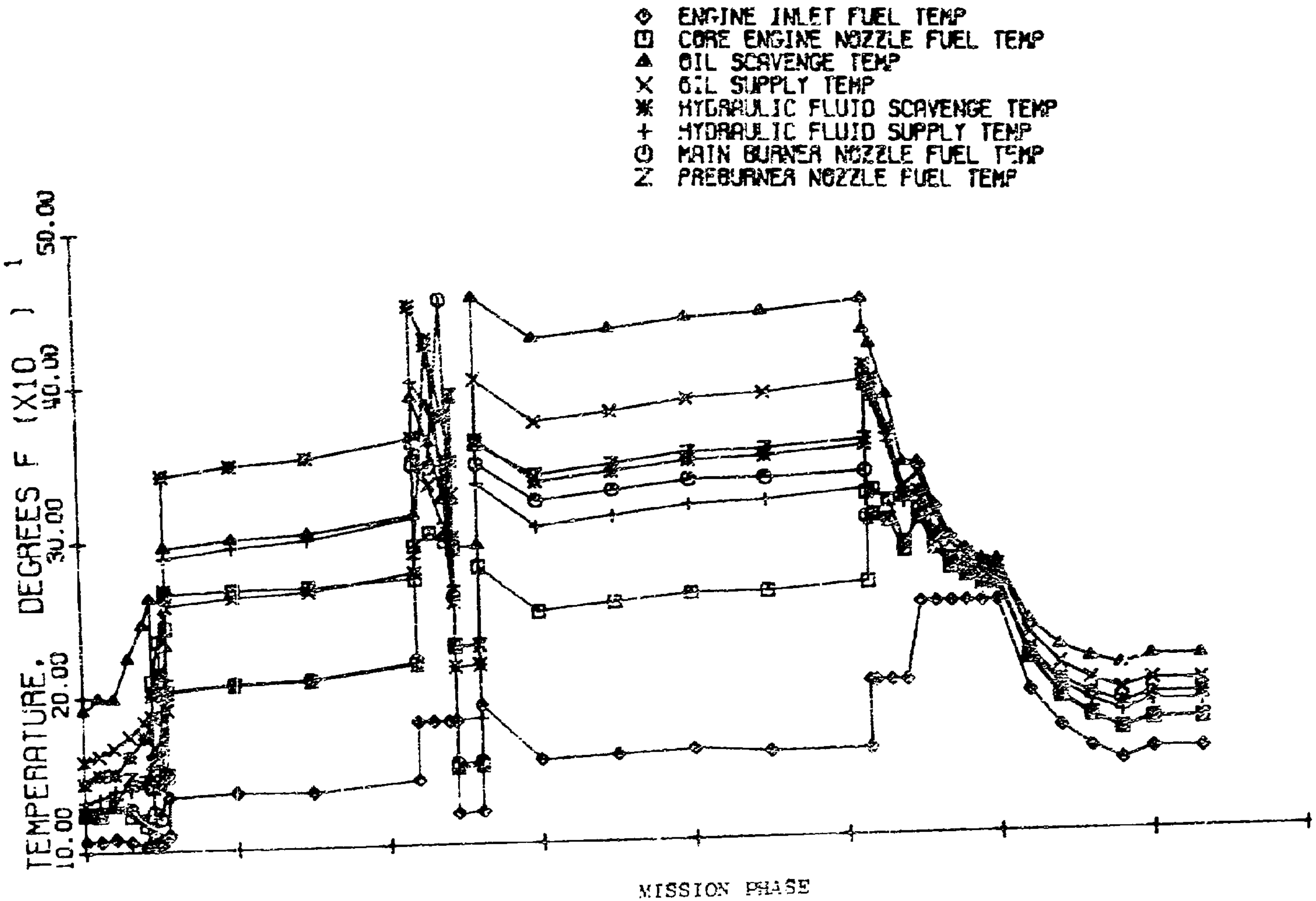



Figure 22. Mission B Baseline Fluid System Thermal Profiles.

The ramjet idle-descent is the more severe of the two flight-idle modes of operation. Recirculation fuel flow is necessary during this 2.5 minute mission phase to maintain the three component systems within their thermal stability limits. This recirculation fuel flow to the aircraft reaches a maximum of 9,000 pph with an engine interface fuel temperature of 180° F. Even with the recirculation and the manifold cooling flows, the ram main burner line does exceed the 325° F level during the ramjet idle-descent. A temperature peak of approximately 425° F is experienced with over-temperature conditions existing during the majority of the descent. As the main burner is in operation during this flight-idle condition and requires little fuel flow, the main burner fuel line is relatively insensitive to the upstream cooling efforts. Although the residence time is short and the maximum fuel temperature not extreme, it should be noted that the unlimited service design limit of 325° F for the JP-5 fuel cannot be guaranteed over the entire mission. Recirculation is not necessary during the final descent to sea level as the core engine fuel flows are sufficient to maintain acceptable system operating temperatures.

C.3 Interceptor Design Characteristics

The Mission B interceptors were designed to a technology level compatible with an anticipated IOC date between 1985 and 1990.

The Mission B interceptor is shown in Figure 23. The interceptors are all in the 80,000 lb. TOGW class with wing area from 1,120 to 1,160 ft$^2$ and a fuel fraction from 0.52 to 0.53. The aircraft has a crew of two, a low aspect ratio delta wing planform with a leading edge sweep of 79.7°. This configuration also uses twin vertical tail surfaces for high speed directional stability and incorporates outboard movable wing tips for pitch and roll control.

The configuration includes two GE14/FLITE turboramjet engines, supplied by freestream (nonaircraft compression field) horizontal ramp mixed compression inlets. A slotted subsonic diffuser is utilized to provide flow to the wrap-around ramjet during operation of that subsystem. Outer walls of the ramjet annulus are designed to include variable area bypass doors.

The primary structure is a cool conventional structure concept thermally protected by an air gap, passive insulation, and external radiative shingles. Cool structure dominates the fuselage; but the wing leading edges, control surfaces, and inlets are hot structure due to their thin cross section. Composite metal matrix structure is used to the maximum practicable extent projected for a mid-to-late 1980 IOC.

Cabin and equipment environmental cooling is provided by a fuel heat sink system using ambient temperature fuel with a vapor cycle refrigeration package to affect the heat transfer.

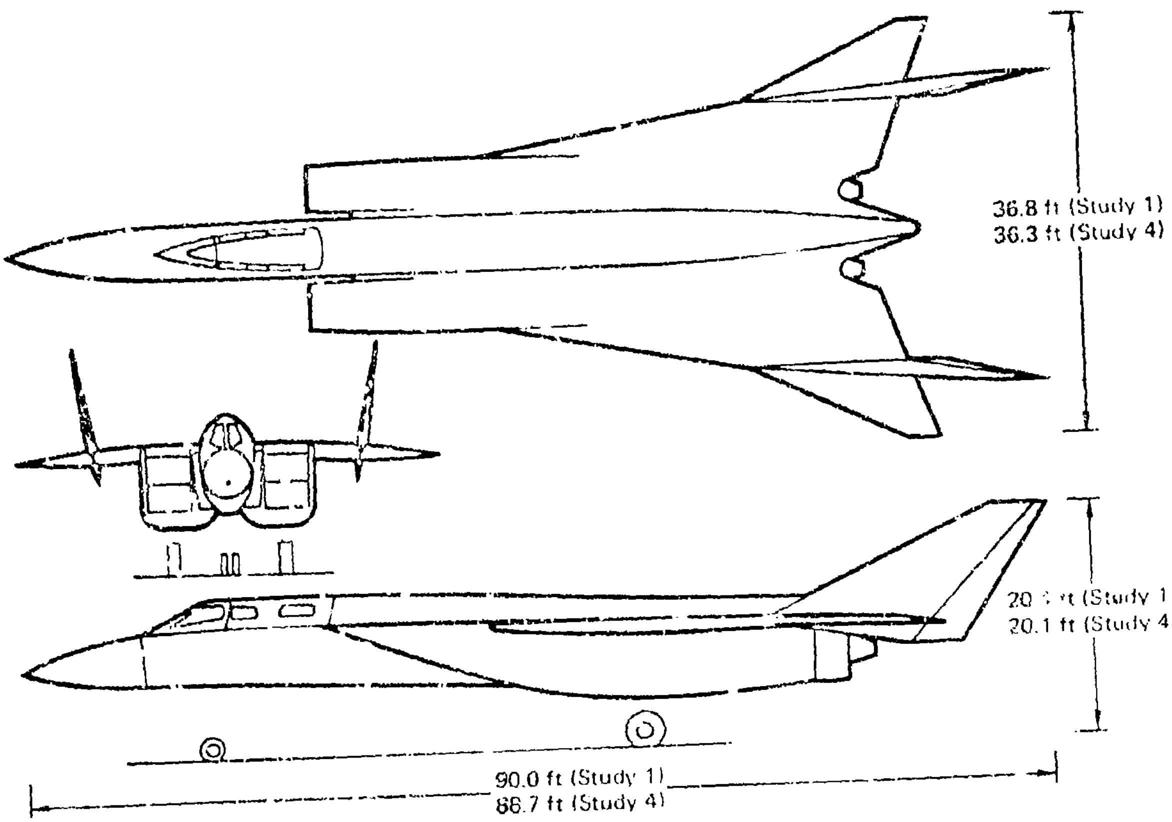



Figure 23. Mission B Aircraft.

The nose cross sectional radius and radome fineness ratio are determined by requirements for a 48 inch-electronically steerable phased array antenna for a long range pulsed doppler radar with multiple-track wide scan capability. The antenna is installed in a look down attitude to provide detection and tracking of both high and low altitude threats.

Aircraft armament is integrated to preserve fuselage fineness. Four long range 500-lb air-to-air missiles and launch systems are integrated into the top of the aircraft using a rotary firing rack or drum. Firing is accomplished out the top to avoid shock interference with the inlets during supersonic missile launch.

C.5 Weight Estimation Techniques

As for Mission A, the structural weights for the Mission B interceptor were determined by conventional methods. Materials for the components were chosen to reflect current and projected material development effort compatible with IOC dates of from 1985-1990. Engine weights were based on GE14/FL1TE scaling data.

The wing torque box and fuselage shell covering is weighed as "cool structure", protected by shingles and insulation. Wing structural weights are based on 3.5 g limit load factor at basic flight design gross weight. Wing secondary structural weight is based on temperatures incurred in the 3.5 g maximum power turn. Rotating tips, vertical tails, and inlets are weighed as hot structure, with design temperatures corresponding to the Mach 4+ cruise environment. The weight for the horizontal rotating tips is included with the wing. Weights for minimum gauge fuselage covering and frames are correlated to the 2,000 psf dynamic pressure climb path. Longerons, stringers, and locally strong areas to react air loads are weighed as a function of the fuselage bending moment and its maximum depth and width. Insulation, included with fuselage weight, is based on the requirement to limit primary structural temperatures to 275° F in the nonfuel areas and allow a 20° F temperature rise in the fuel areas. Landing gear weights are based on the 2.0 g taxi load at maximum design gross weight. Air induction system weights are based on ultimate duct pressures of 195 psi and design temperatures corresponding to the cruise condition.

A high percentage of metal matrix composites materials (boron aluminum and graphite nickel) is used in the design. These provide a substantial payoff in terms of reduced aircraft size and weight. Boron aluminum is used for the primary fuselage and those wing areas which are protected by insulation and radiative shingles. Hot structural components are designed using graphite nickel. The relatively high temperatures in the cruise environment precludes the use of other materials for passively cooled concepts, with the exception of René 41. Supplemental studies allowed determination of the merits of active cooling in the inlet area as discussed in Section V.

## C.6 Propulsion System Performance

The propulsion system for the Mission B vehicle consists of the GE14/FLITE-2A turboramjet engine and nozzle matched to a mixed compression inlet. Engine variations for the fuel and lubricant combinations corresponding to the Mission B studies are presented in Section V.

### GE14/FLITE-2A Engine and Nozzle

The GE14/FLITE-2A engine consists of a stoichiometric turbojet with a wraparound ramjet. The core turbojet incorporates a transonic compressor, a carbureting-type combustor, and a single stage, variable geometry turbine. The wraparound ramjet incorporates a preburner and a main burner, both of which use carbureting injection. The nozzle is a variable-geometry, converging-diverging design designated as a "terminal fairing ejector nozzle."

### Air Induction System Performance

The air induction system consists of a horizontal, two-dimensional, mixed-compression, double external ramp inlet. The inlet incorporates variable external ramp geometry which is scheduled as a function of flight Mach number. The first ramp is fixed and the second ramp is hinged. The shock structure at the design point consists of two oblique shocks from the external ramps, a series of intersecting internal oblique shocks which form a double shock train, and a terminal normal shock. The oblique shocks decelerate the airflow to a throat Mach number of 1.35 where the terminal normal shock is located. The flow is then decelerated subsonically to the engine face. The length of the subsonic diffuser was determined by specifying that the total included angle, between straight lines joining the throat exit with the engine face, not exceed 13°. A bypass system was included in the design for inlet and engine airflow matching. The inlet operates in an external compression mode from Mach 0 to 1.8 and in a mixed compression (external and internal) mode from Mach 1.9 to the design Mach number.

## C.7 Thermodynamic Characteristics

### Design Temperatures

Aerodynamic heating effects during the Mach cruise phase produce the most severe sustained thermal environment for both the upper and lower surfaces of the aircraft. The maximum surface temperatures, presented in Figure 24, were computed at cruise conditions with a nominal angle of attack. These maximum external surface temperatures are used to assist in the selection of airframe structural materials and size thermal protection requirements.

### Thermal Protection System

The Mission B interceptors are designed to employ a protected structural concept wherever possible. The thermal protection system concept consists of an external shingle backed by insulation with an internal air gap. The shingle is treated to obtain a high surface emissivity enabling reradiation of heat away from the surface to minimize surface temperatures. An air gap provides a

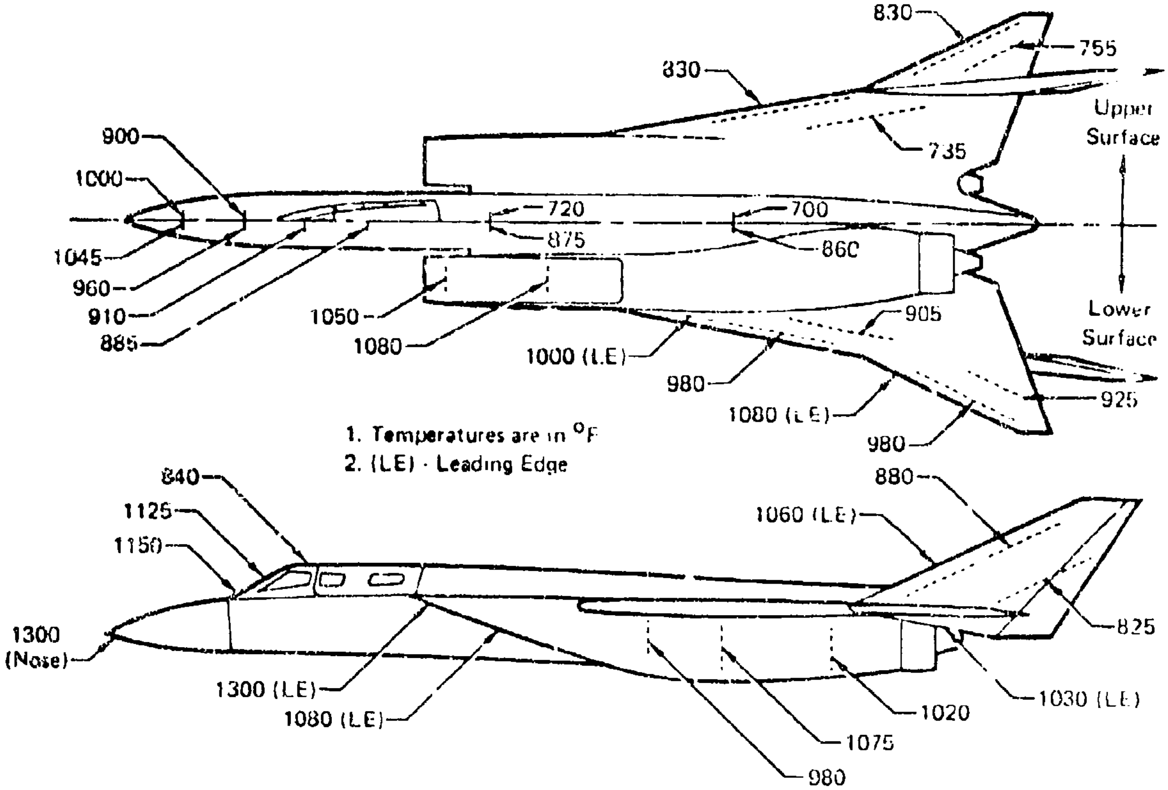



Figure 24. Cruise Surface Temperature Distribution, Mission B Interceptor.

radiation barrier to heat transfer (surfaces on either side of the gap displaying low emissivity characteristics). Lightweight, flexible insulation is used to minimize thickness, thereby maximizing usable aircraft volume. In nonfuel areas, the insulation is sized to limit the maximum primary structure temperatures to 275° F. In fuel tank areas, the insulation is sized to limit the stored fuel temperature rise to 20° F due to aerodynamic heating effects. Since all thermally sensitive compartments are located in regions of the aircraft where the protected structural concept is employed, additional internal insulation provisions (except for the crew compartment) are unnecessary.

### Airframe Heat Loads

Airframe heat loads that must be absorbed by the fuel before delivery to the engines are summarized in Table VI as a function of mission phase. Hydraulic and electrical system heat loads are based on system power requirements ranging from 120 to 520 pph. Hydraulic heat loads include internally generated heat (due to pump inefficiencies) and environmental heating to actuator and lines located in uninsulated regions of the aircraft. Heat rejection to the fuel from the ECS is a function of aerodynamic heating effects and the mode of radar operation. Since fuel is used exclusively as the heat sink for the Mission B ECS concept, a requirement for fuel cooling of the ECS exists throughout the mission.

Table V. Summary of Heat Loads to Fuel Mission B Interceptor

| | Heat Load (Btu/min) | | | |
|---|---|---|---|---|
| Mission Phase | Environmental Control Systems | Hydraulic System | Electrical System | Boost Pumps |
| Takeoff/Climb | 1,800-4,210 | 3,960-7,580 | 940 | 110-370 |
| Outbound Cruise | 4,210-4,310 (a)<br>2,980-3,110 (b)<br>4,450-4,600 (c) | 7,580-7,220 | 940 | 60 |
| Descent to 65,000 ft | 4,600-4,050 | 7,220-4,740 | 940 | 110 |
| Turn | 4,050 | 4,740 | 940 | 110 |
| Inbound Cruise | 4,050-4,060 (a)<br>2,730-2,810 (b)<br>1,880-1,920 (c) | 4,740-4,590 | 940 | 70 |
| Descent to Sea Level | 1,920-1,280 | 4,590-3,960 | 940 | 100-70 |
| Loiter | 1,280-1,160 | 3,960 | 940 | 80 |

(a) Radar On
(b) Radar on Standby
(c) Radar Off

### Environmental Control System

The Mission B ECS, presented in Figure 25, is a vapor cycle using fuel, as the primary heat sink. As indicated, the airframe heat loads are absorbed by an intermediate heat transport (coolant) loop which transmits these loads to the fuel via a vapor cycle refrigeration package. Analyses, based on the airframe heat loads as summarized in Table V, and engine fuel flowrate data indicates that this concept is compatible with the total range of engine/airframe fuel interface temperatures (150 - 350° F) investigated in this study. During low fuel flow periods such as descent, sufficient fuel is circulated through the airframe heat exchangers to absorb all the heat loads without exceeding the prescribed interface temperature. Fuel flow in excess of engine requirements is recirculated back to the feed tank. Use of the vapor cycle concept imposes an additional consideration; the fuel temperature entering the ECS condenser must be sufficiently low to permit efficient cycle performance. The condenser inlet fuel temperature is maintained below 115° F. For those cases where bulk temperature limits may be exceeded, optional peak heat load relief is desirable. The representative system considered here is a simple evaporator. As shown in Figure 25, a water boiler and a ram air heat exchanger are located between the feed tank and the ECS condenser. During cruise at high altitudes, fuel is routed through the water boiler after the feed tank bulk fuel temperature exceeds 115° F. Fuel cooling via water boiling is used through the early phases of descent until an altitude is reached where the required boiling temperature of 115° F is exceeded (approximately 50,000 ft). Ram air temperatures, at this stage of the mission are sufficiently low to provide an adequate heat sink for fuel cooling.

## D. FLUID PROPERTIES

### D.1 Fuel Properties

The FL¯TE program encompassed studies of system designs using four different fuels: JP-4, JP-5, JP-7, and JP-8. All of these are mixtures of hydrocarbons, hence their bulk chemical properties are very similar. The major differences are in volatility and thermal stability. JP-4 is quite volatile, whereas the other three fuels have relatively low and similar volatilities. JP-7 has high thermal stability, whereas, the other three fuels can have relatively low thermal stabilities. Their specified minimum thermal stabilities are, in fact, identical.

All of these fuels are procured to specifications which are as broad as possible within the quality levels desired to achieve adequate availability at minimum cost. Therefore, some of the fuel physical properties can vary widely depending on the world-wide sources of the fuels. For design purposes, it was considered preferable to use the best available average data, rather than extremes.

For the JP-4 and JP-5 fuels, average data were obtained from Reference 2. Since JP-8 has not yet been produced in large volume, data on its properties were not available. However, Jet A-1 is its commercial equivalent, and

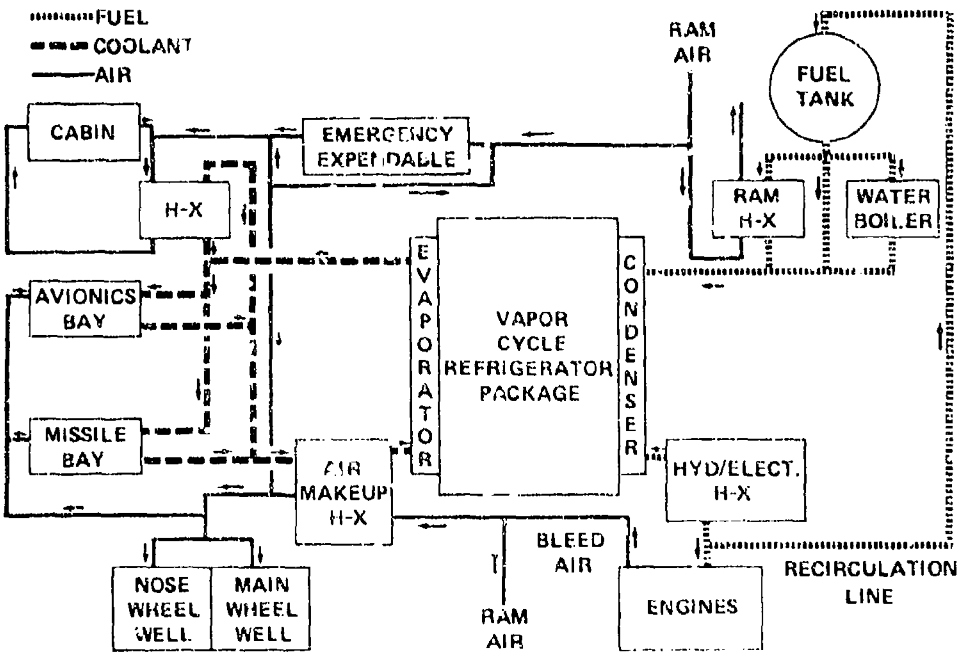



Figure 25. Mission B Interceptor ECS Schematic.

average data on its properties were obtained also from Reference 1. JP-7 has been produced in very limited quantities, and published data on multiple sources were not available. Therefore, typical data on a single batch produced by a major refiner were used, as published in Reference 2.

The data on density variation with temperature were derived from information in Reference 3.

The data on viscosity were based on average properties in Reference 6, and established slopes for viscosity curves from Reference 4.

The specific heat data were calculated using the method given in Reference 5. The accuracy is believed to be within 4 percent of the true values. Although the data are considered not applicable below 0° F and above 475° F (350° F for JP-4), they were applied wherever possible.

The thermal conductivity curve is the average of data from References 6, 7 and 8. Experimental data are very scarce at moderate temperatures, and those which are available are not of high quality. Data at high temperatures were virtually nonexistent. The accuracy of the plotted curve may be no better than 15 percent of the true values.

The vapor pressure data were calculated using the method given in Reference 9. The accuracy of the calculated data has not been evaluated. However, the reproducibility is considered no better than 2 psi or 8 percent of the mean of two results, whichever is greater.

Plotted values of density, viscosity, specific heat, thermal conductivity, and vapor pressure are shown in Figures 26 through 30.

The enthalpy of the four fuels was computed using the following equations, which were derived from the specific heat data. These are applicable only while the fuels are in the liquid state.

For JP-4: $H = 44.6 \times 10^{-2} T + 2.91 \times 10^{-4} T^2$ (4)

For JP-5: $H = 42.4 \times 10^{-2} T + 2.79 \times 10^{-4} T^2$ (5)

For JP-7: $H = 44.0 \times 10^{-2} T + 2.88 \times 10^{-4} T^2$ (6)

For JP-8: $H = 42.9 \times 10^{-2} T + 2.32 \times 10^{-4} T^2$ (7)

where, H = enthalpy in Btu/lb and
T = temperature in ° F

The heats of combustion used for the four fuels are listed in Table VI.

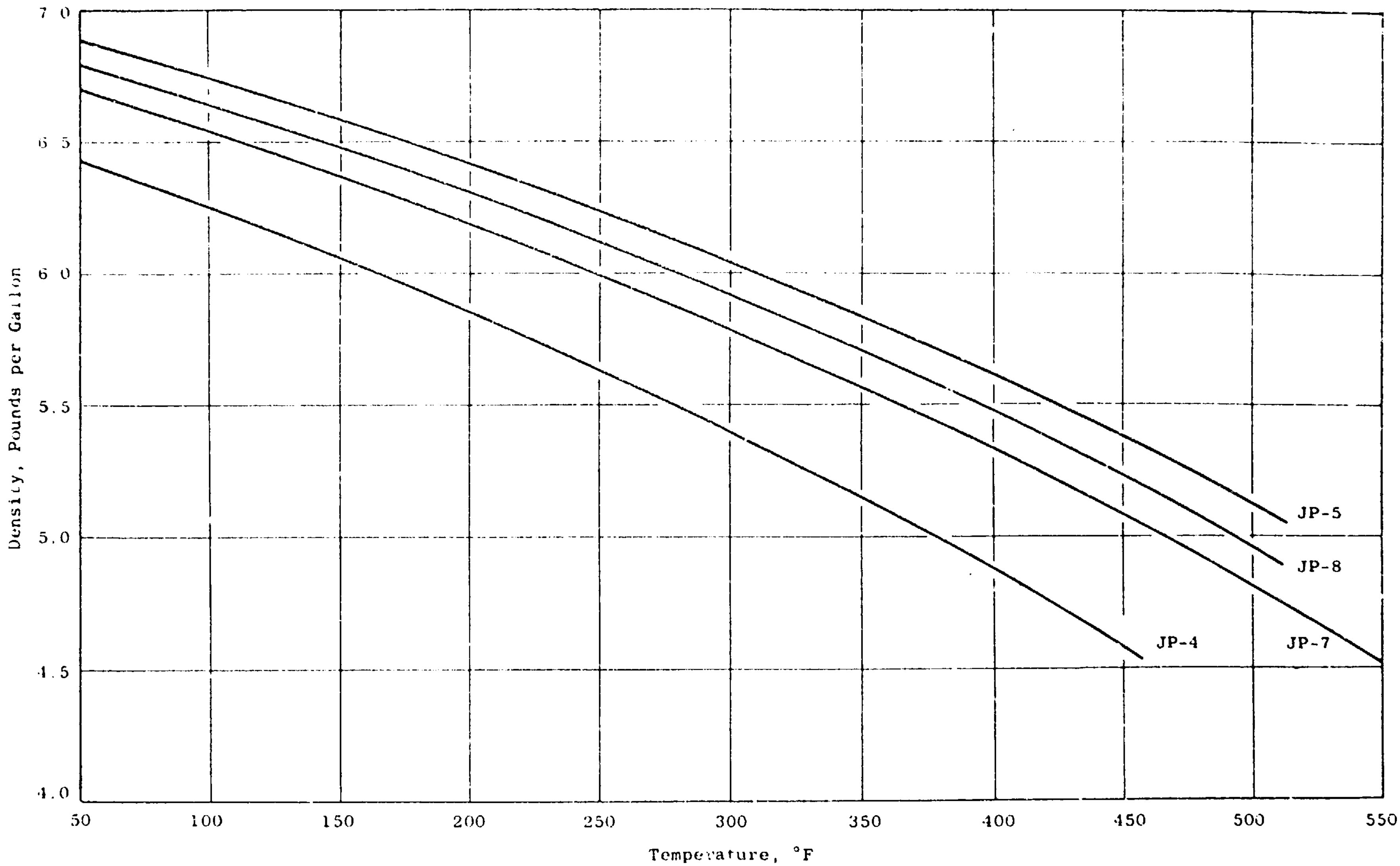



Figure 26. Densities of Fuels Used in FLITE Program.

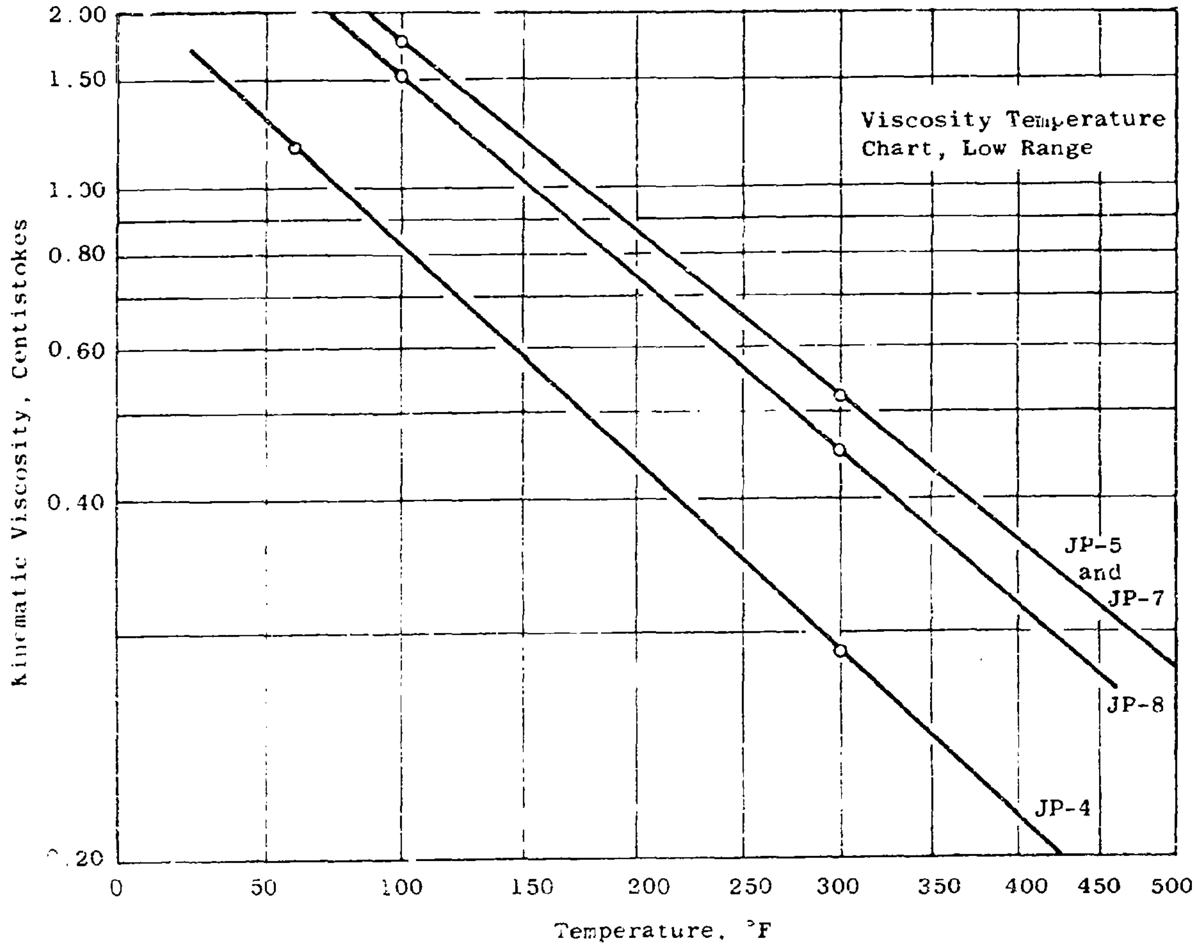



Figure 27. Viscosities of Fuels Used in FLITE Program.

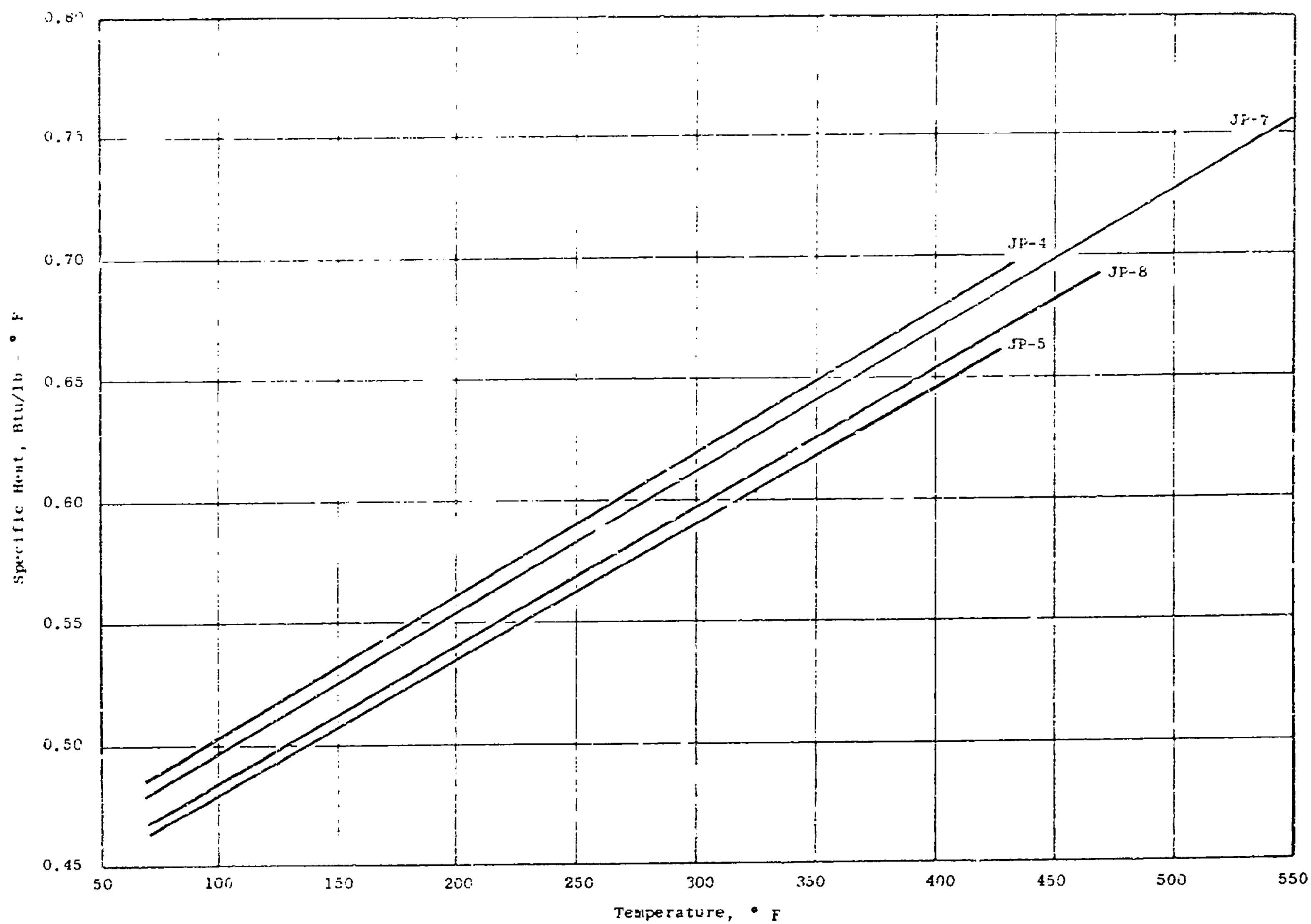



Figure 28. Specific Heats of Fuels Used in FLITE Program.

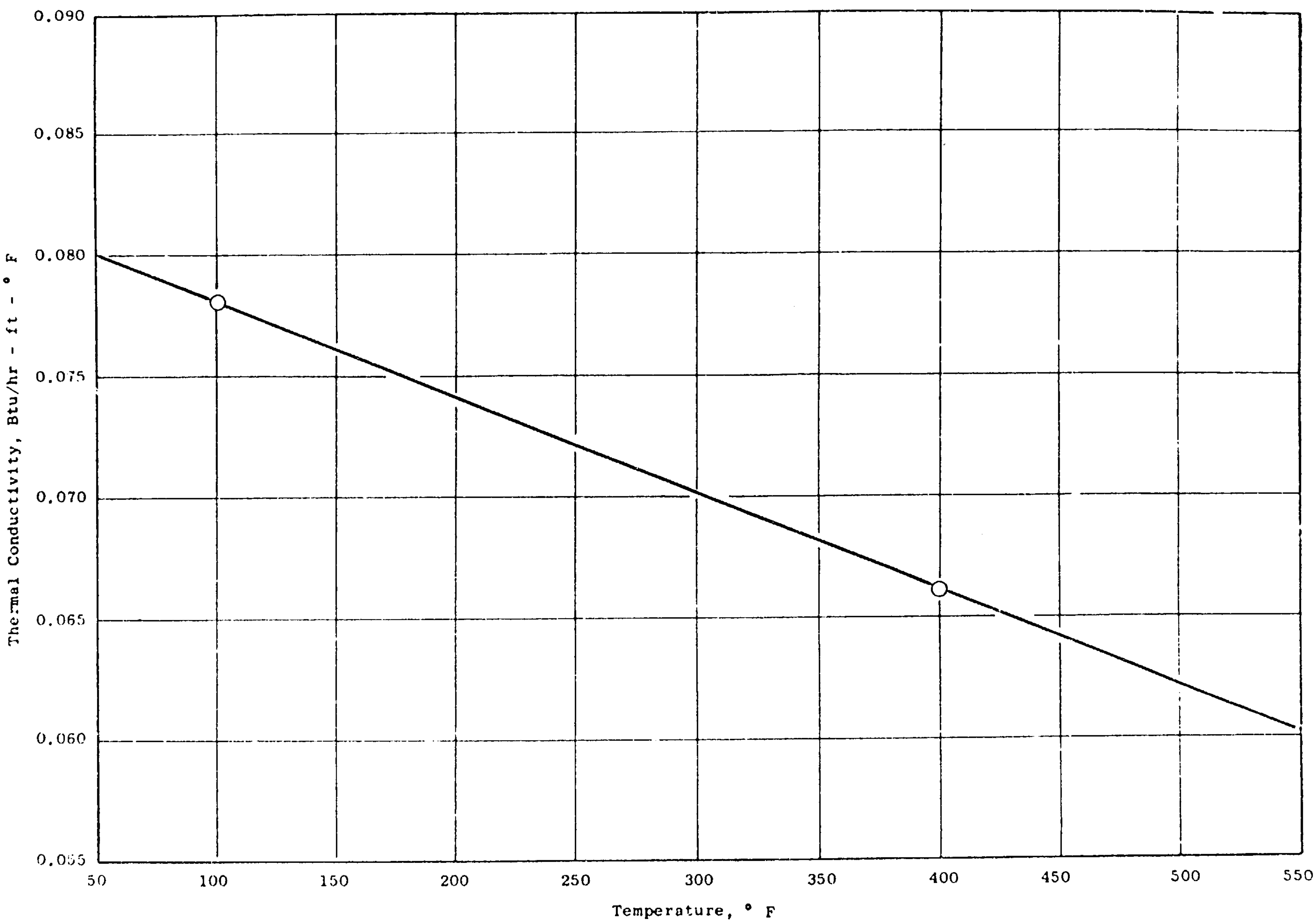



Figure 29. Thermal Conductivites of Fuels Used in FLITE Program.

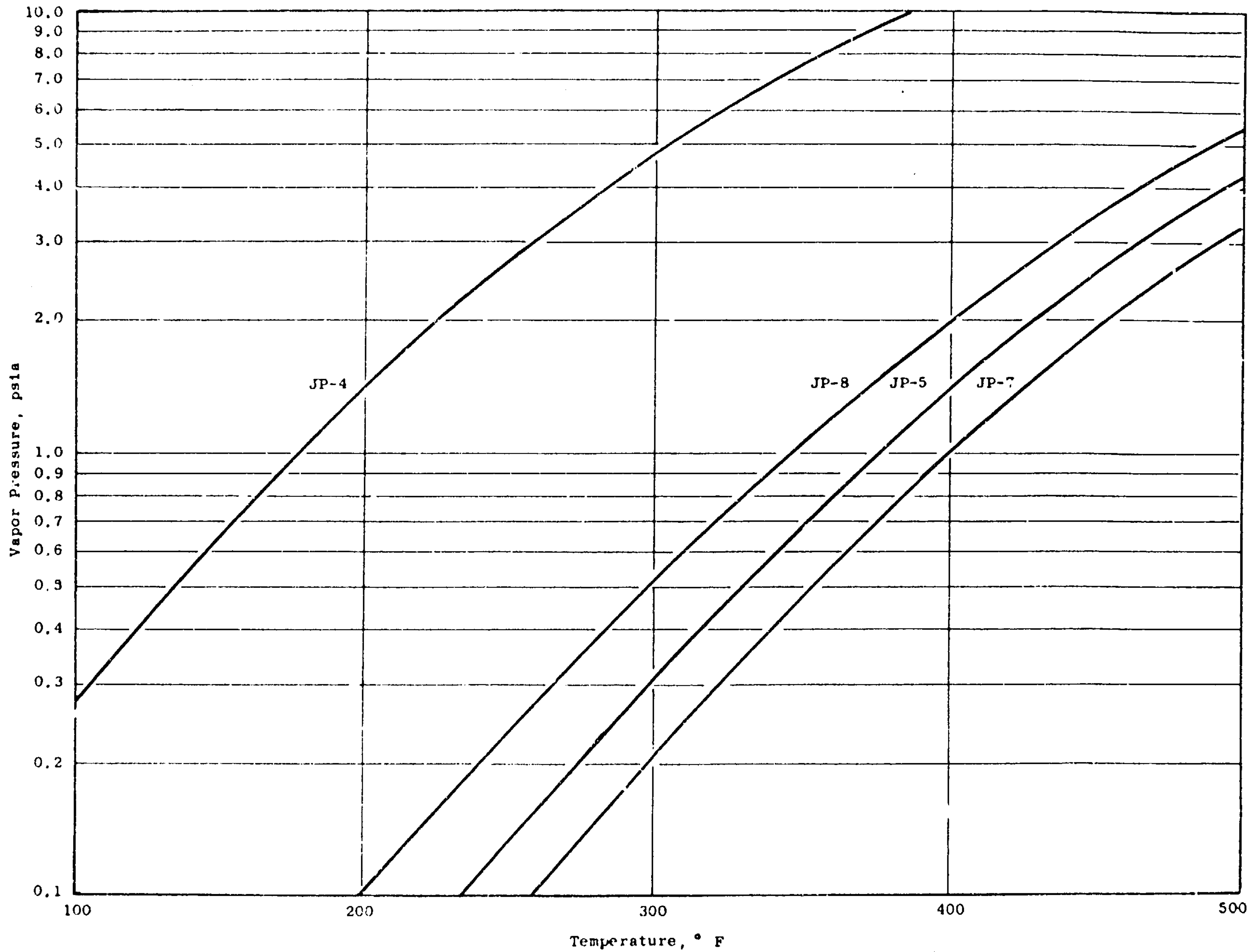



Figure 30. True Vapor Pressures of Fuels Used in FLITE Program.

Table VI. FLITE Program Fuels
Lower Heats of Combustion

| Fuels | Heat of Combustion |
|---|---|
| JP-4 | 18,700 Btu/lb |
| JP-5 | 18,500 |
| JP-7 | 18,700 |
| JP-8 | 18,550 |

The thermal stability limits of the four fuels were considered at three operational levels; unlimited service, limited service (cleanable after several missions) and research level. These limits are presented in Table VII.

Table VII. FLITE Program Fuels Thermal Stability Limits

| Fuel | Thermal Stability Limit: Unlimited Service | Limited Service | Research Level |
|---|---|---|---|
| JP-4 | 325° F | --- | --- |
| JP-5 | 325 | 475 | --- |
| JP-7 | 550 | 700 | 1000° F |
| JP-8 | 325 | 475 | --- |

Although the original program concept was to use the unlimited service fuel thermal stability limits, the operational characteristics of the Mach 4+ interceptors and the search for maximum use of available heat sink in both the Mach 3+ and Mach 4+ interceptors dictated the definition of the higher levels. Evidence to support the limited service values was gathered through the examination of laboratory test (MINEX) results from a substantial number of tests on the thermal stabilities of JP-type fuels.

Extablishment of the research level of 1000° F for JP-7 fuel was principally the result of tests documented in Reference 15 in which highly refined JP-5 was elevated to temperatures of this order of magnitude for short residence time tests. Acceptance of this level permitted the definition of a heat exchanger design for the Mach 3+ interceptor that produced significant improvements in mission performance. In the absence of JP-7 data at these elevated temperatures, JP-5 data as defined in Reference 10 were substituted. Liquid data were utilized up to the critical point of 750° F where the transition was made to vapor phase data. The accuracy of these data would, of course, be highly questionable, but they were deemed acceptable for the definition of potential to which use they were applied.

D.2 Lubricant Properties

The contractual work statement required that the following lubricants be evaluated in the course of the program:

| | |
|---|---|
| o MIL-L-27502 | 425° F BOT |
| o Hypothetical ester | 500° F BOT |
| o Polyphenyl ether | 575° F BOT |
| o Perfluorinated polyether | 650° F BOT |

In order to quantify the effects of lubricant properties on engine design, it was necessary to establish specific characteristics for each oil. Technical representatives of major lubricant suppliers were contacted to discuss the current status of these lubricants, particularly with respect to polyphenyl ethers and perfluorinated polyethers.

For purposes of the study a representative fluid was chosen as realistically as possible within each category on which the maximum amount of property data are available. Rationale for fluid selection within each class are given as follows:

- MIL-L-27502. This specification represents a class of synthetic ester-base lubricants of high oxidative stability. Because the specification is still conceptual, average lubricant properties of real ester-base fluids (in most cases MIL-L-23699, but including MIL-L-27502 candidate oils) were assumed.

- 500° F Hypothetic Ester. In order to assess the effect of higher bulk oil stability only, properties were assemed to be identical with MIL-L-27502, but with higher bulk oil stability (500° F rather than 425° F).

- Polyphenyl Ether. The properties of "Skylube 600"* polyphenyl ether were selected as a design basis. A chemical variation known as a "C-ether" appears to have a better overall balance of properties; however, physical properties are less well established.

- Perfluorinated Polyether. Prominent among this class of fluids are the hexafluoropropylene epoxide (HFPO) polymers, marketed by Du Pont under the trade name "Krytox"** fluids, and by Montecatini-Edison S.P.A. "Fómblin"*** fluids. Several viscosity grades, differing in polymer length, are available. Du Pont has developed another variation based upon triazine, known as the HFPO-triazine fluids. These promise to be eventually lower in cost with practically the same capabilities as the HFPO polymers. The properties of Krytox 143AC were selected for the design comparison.

---

*Trademark Monsanto Company
**Trademark DuPont Company
***Trademark Montecantini-Edison

A necessary task of the program was to establish the pertinent properties of these lubricants. Design curves giving nominal properties were developed for the following properties, all versus temperature:

- Viscosity
- Specific gravity
- Thermal conductivity
- Specific heat
- Vapor pressure
- Isentropic tangent bulk modulus

These curves are presented in Figures 31 through 38.

The source references and the assumptions inherent in the generation of these property data are summarized as follows for each of the four lubricants:

MIL-L-27502

| | Source References |
|---|---|
| Viscosity. Design curve is based on MIL-L-27502 limits of 17,000 cs. max. at -40° F and 1.0 cs. min. at 500° F. | (11) (12) |
| Specific Gravity. Curve is based on an average of several 5-centistoke oils including MIL-L-27502 candidate oils. | ---- |
| Thermal Conductivity. Curve is based on least squares average of data from vendor sources on various ester-base oils including MIL-L-27502 candidate oils. | ---- |
| Specific Heat. Curve is based on an average of several "Type 2" oils, including a MIL-L-27502 candidate oil. Note that MIL-L-27502 limits are considerably lower than typical values for real oils. | ---- |
| Vapor Pressure. Curve is based on MIL-L-23699 average derived from ASTM D972 Evaporation Loss data. | ---- |
| Bulk Modulus, Isentropic Tangent. Curves are based on a MIL-L-23699 oil, run by the method of MIL-H-27601 (P-V-T method) by Midwest Research Institute, General Electric Proprietary data. Data agree well with similar data determined on a MIL-L-9236B oil. | ---- |

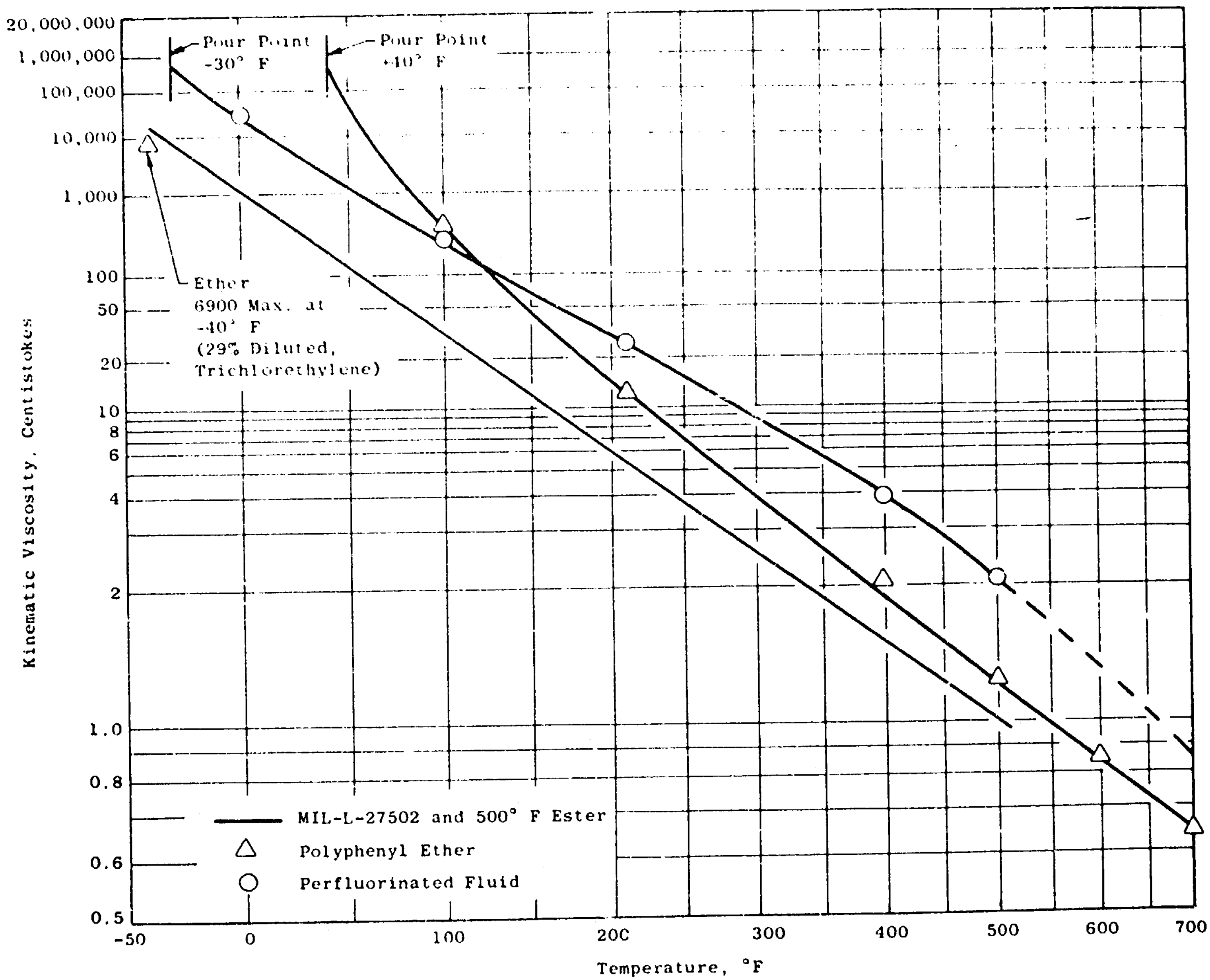



Figure 31. Viscosities of Lubricants Used in FLITE Program.

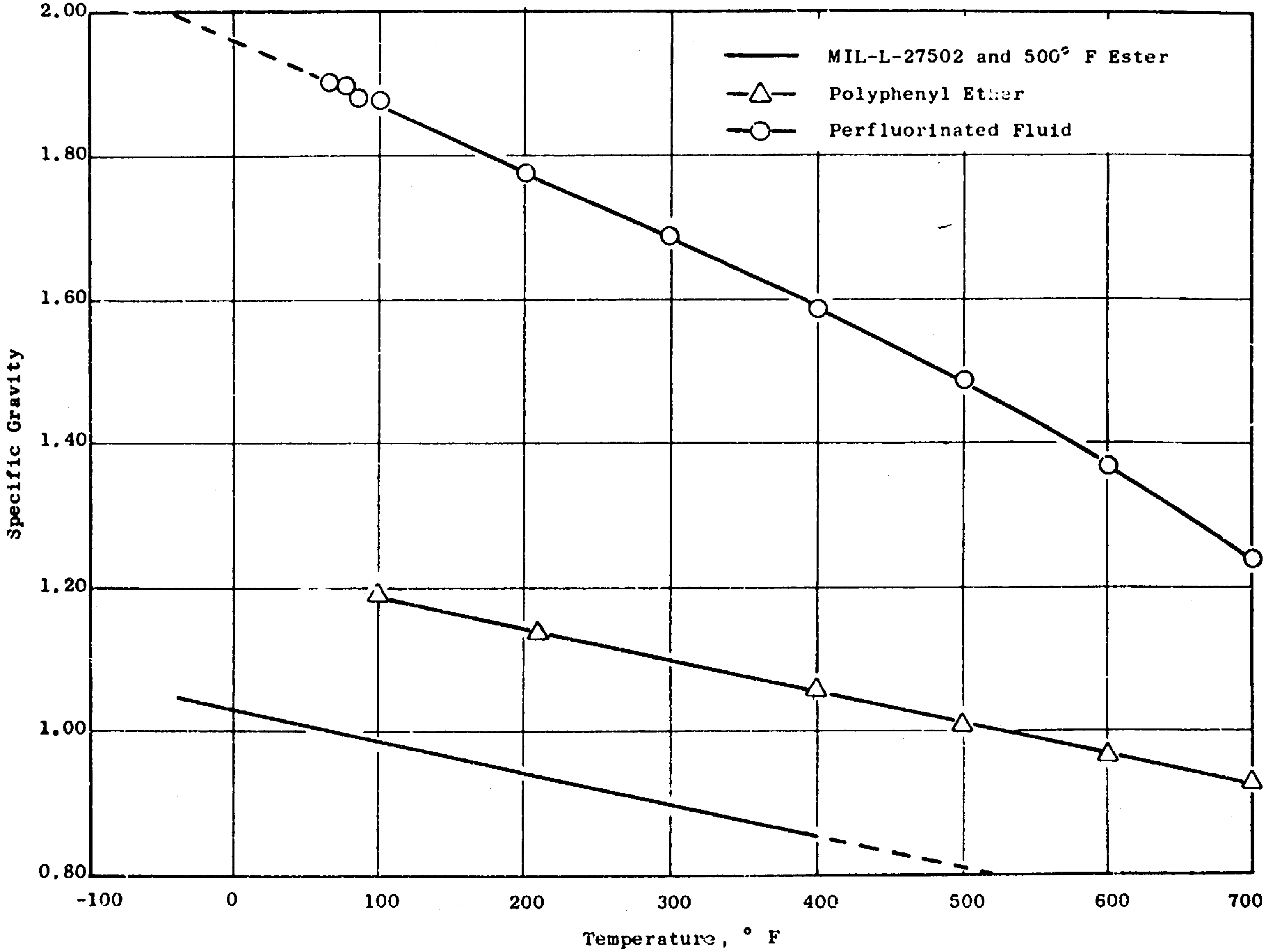



Figure 32. Specific Gravities of Lubricants Used in FLITE Program

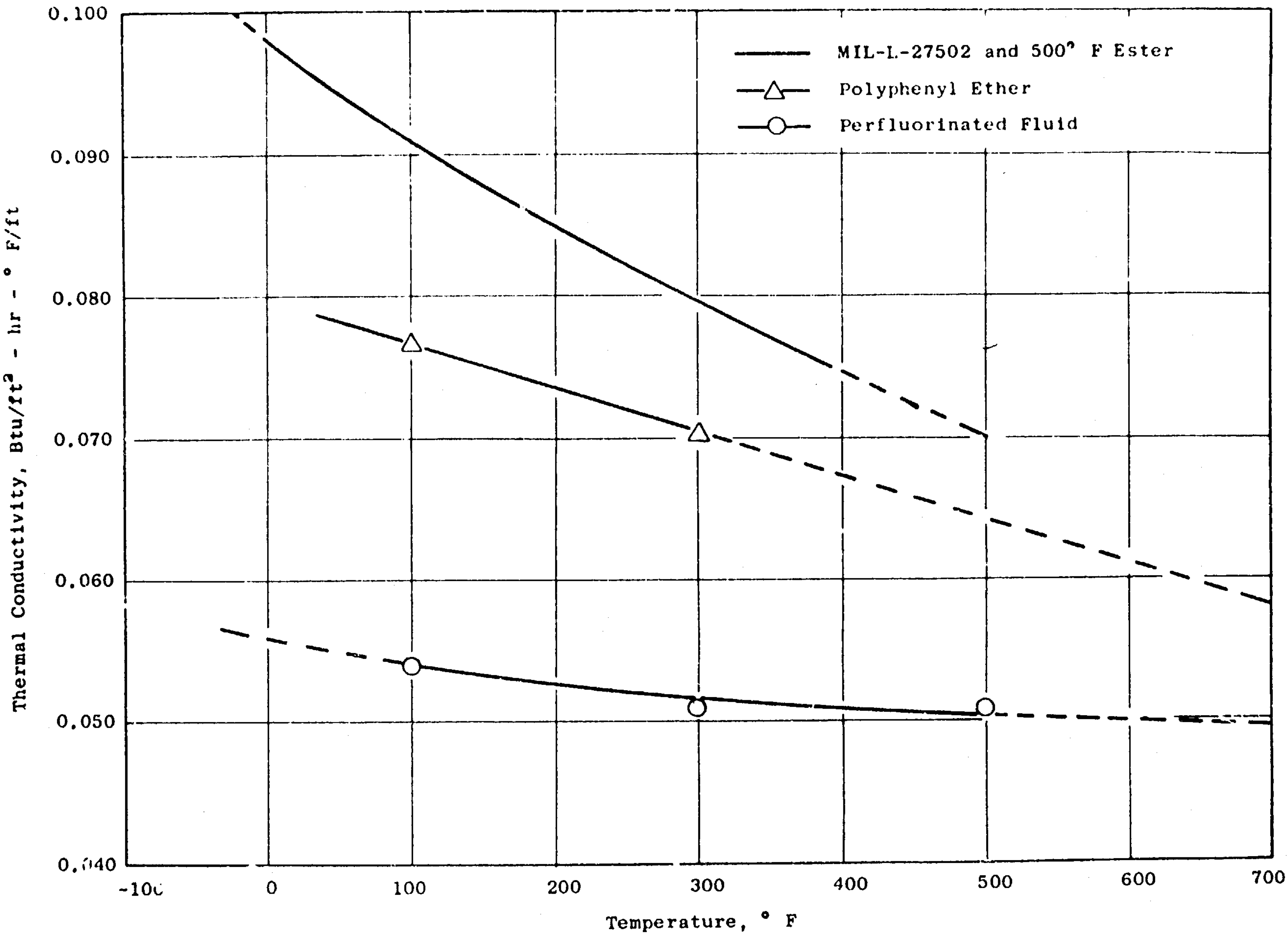



Figure 33. Thermal Conductivities of Lubricants Used in FLITE Program.

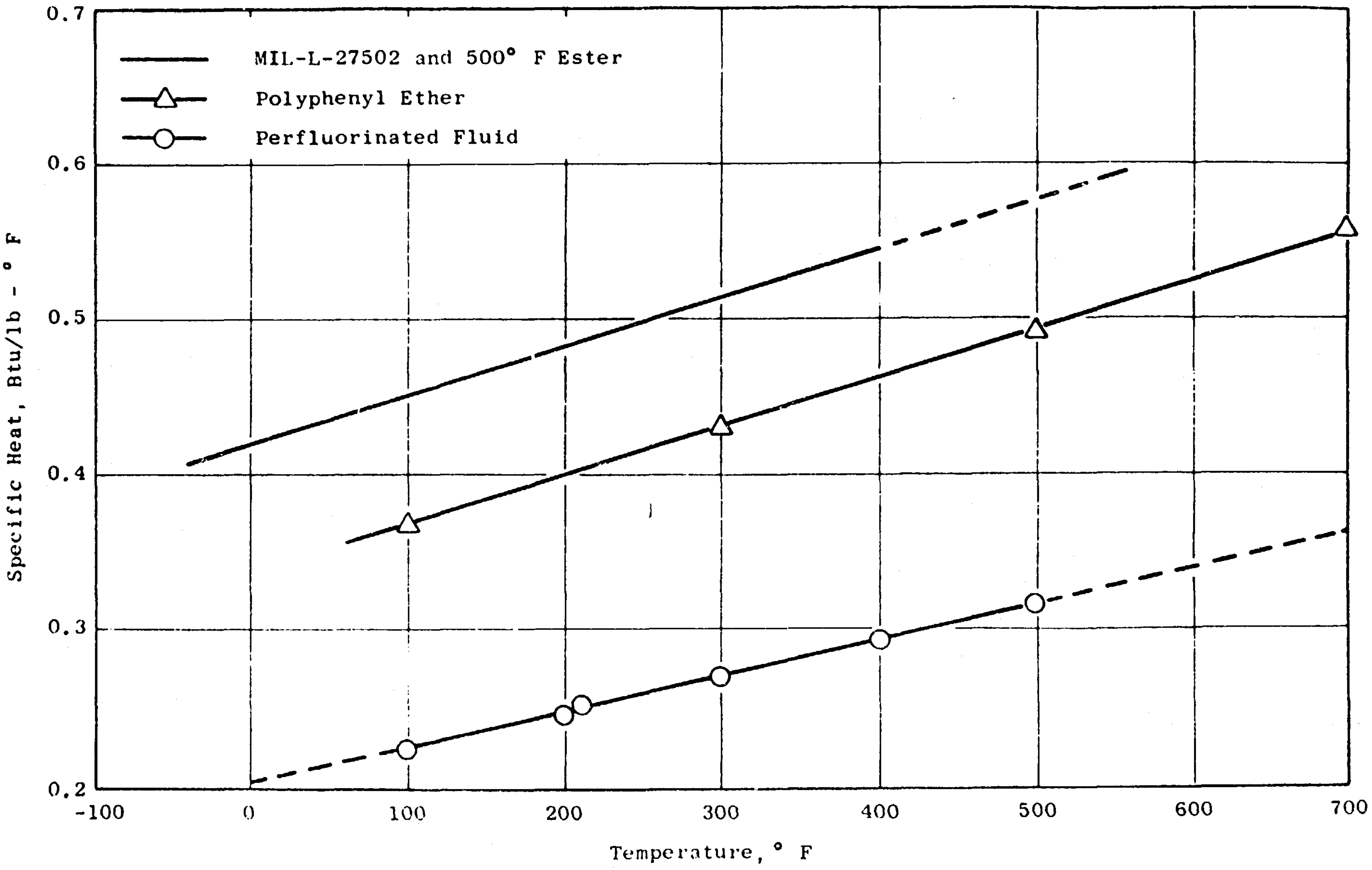



Figure 34. Specific Heats of Lubricants Used in FLITE Program.

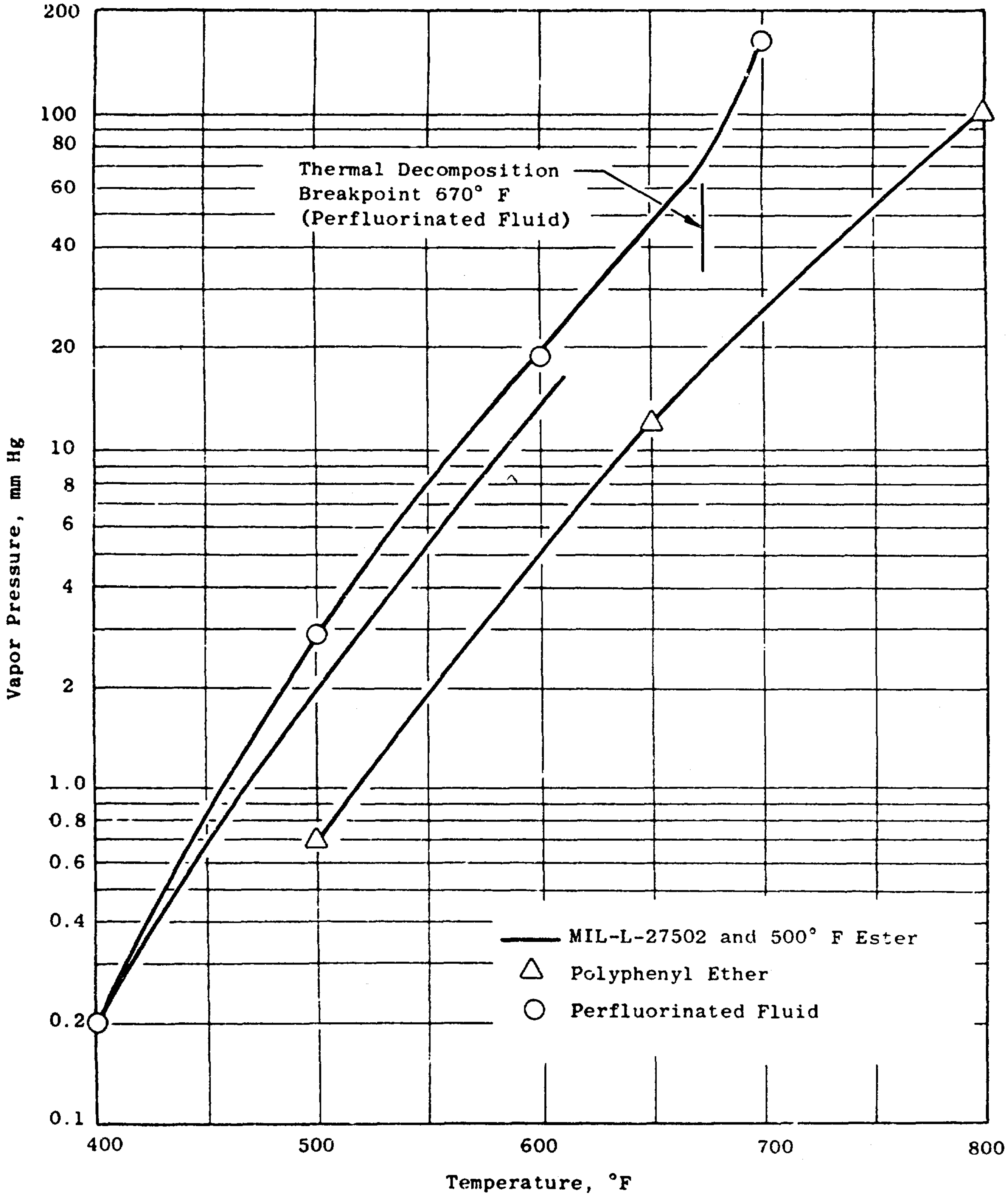



Figure 35. Vapor Pressures of Lubricants Used in FLITE Program.

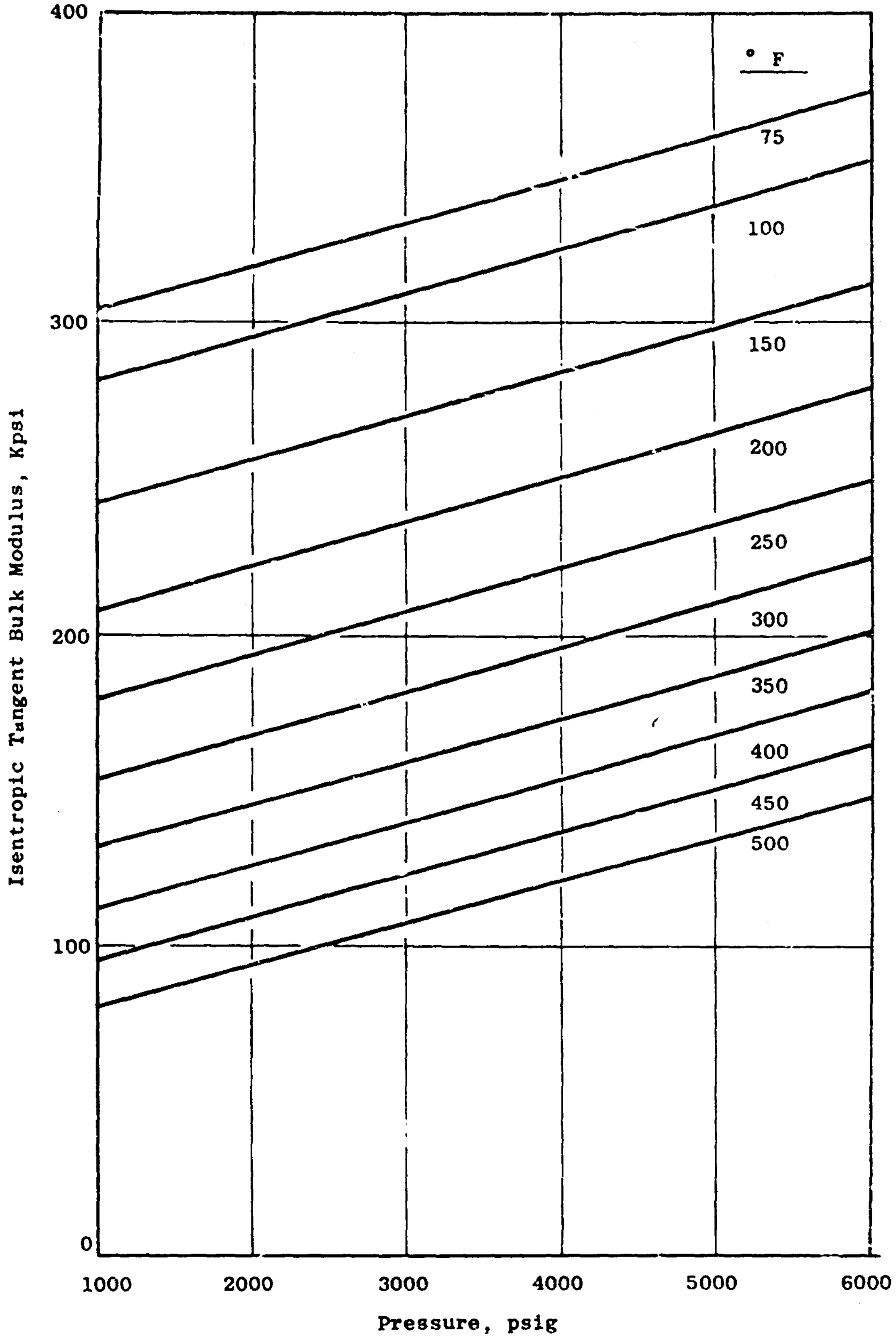



Figure 36. Bulk Moduli of MIL-L-27502 and 500° F Esters.

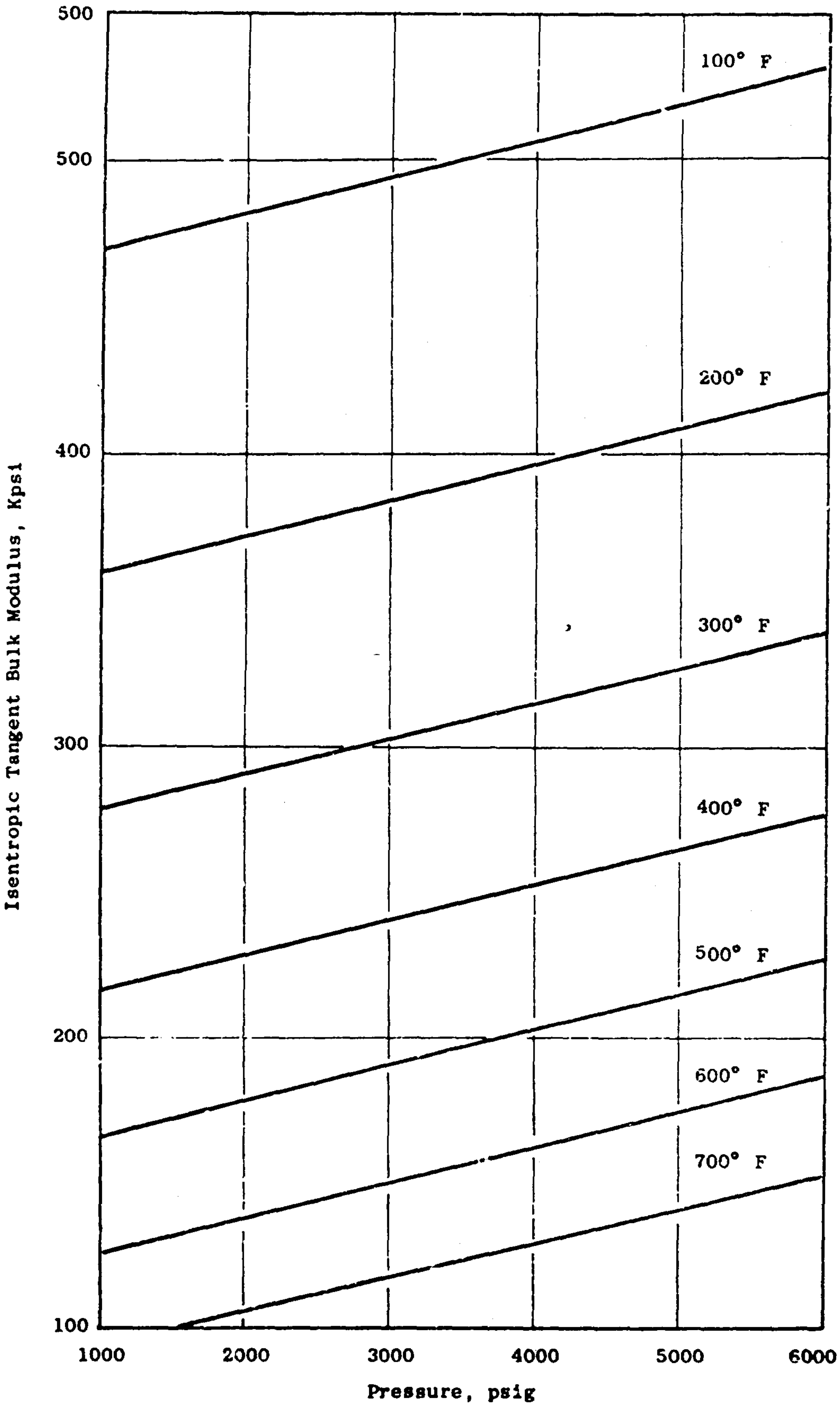



Figure 37. Bulk Modulus of Polyphenyl Ether.

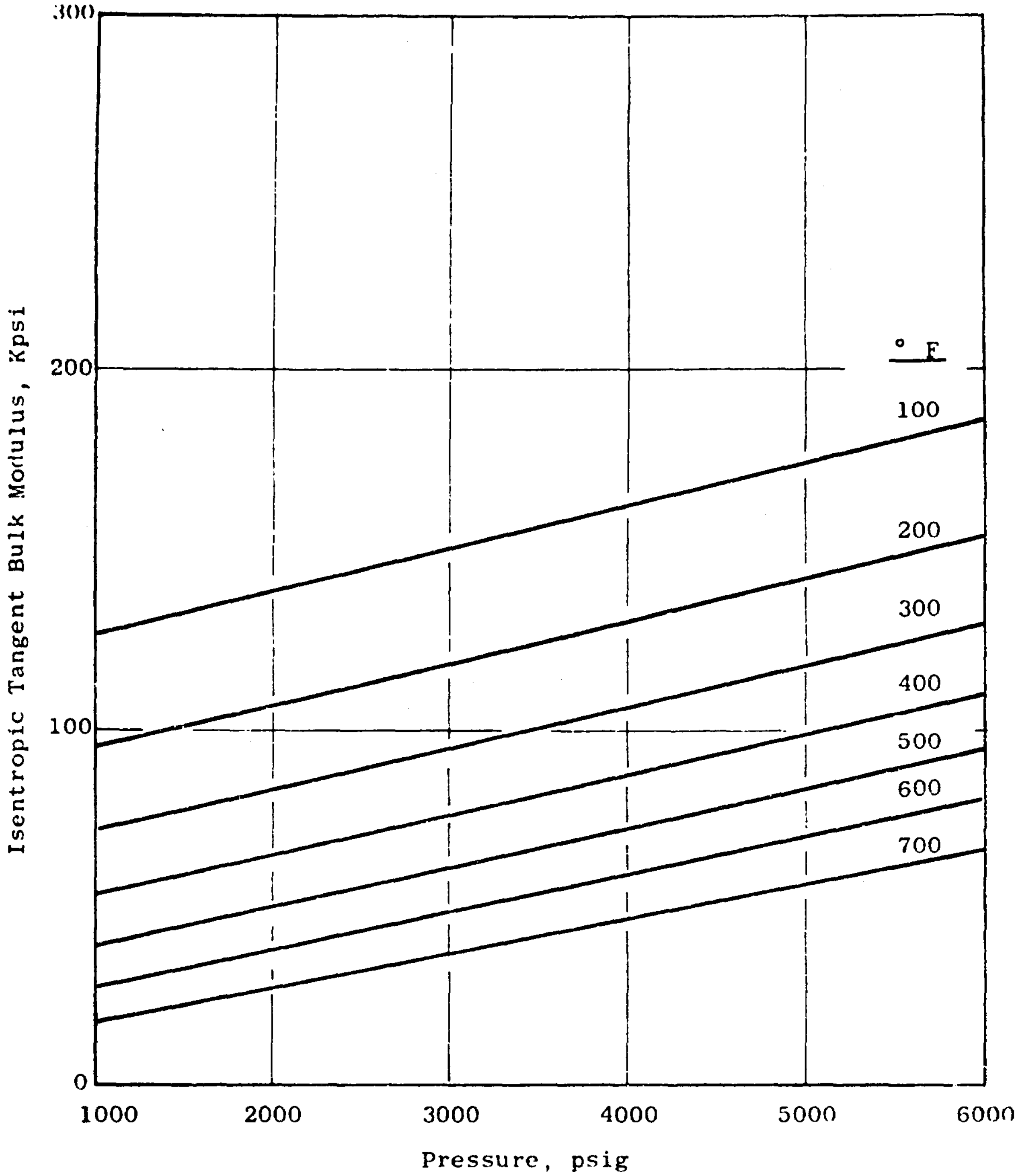



Figure 38. Bulk Modulus of Perfluorinated Fluid.

Note that bulk modulus data on all fluids were derived from isothermal tangent bulk modulus ($B_t$) data determined by Midwest Research. In all cases, isentropic tangent bulk modulus ($B_s$) was calculated by multiplying by $\gamma = C_p/C_v$. $\gamma$ was assumed to be 1.12 in all cases. Therefore $B_s = 1.12\ B_t$.

| 500° F Hypothetical Ester | Source References |
|---|---|
| All six properties are assumed identical to that of MIL-L-27502, as explained above. | ---- |

Polyphenyl Ether (Skylube 600, 5P4E)

| | |
|---|---|
| Viscosity | (12) (13) (14) |
| Specific Gravity | (13) |
| Thermal Conductivity | (13) |
| Specific Heat | (13) |
| Vapor Pressure (isotheniscope) | (13) |
| Bulk Modulus, Isentropic Tangent | (15) |

Perfluorinated Polyether (Krytox 143AC)

| | |
|---|---|
| Viscosity | (16) |
| Specific Gravity | (15) (16) |
| Thermal Conductivity | |
| Specific Heat | (16) (17) |
| Vapor Pressure (Isoteniscope) | (16) |
| Bulk Modulus, Isentropic Tangent | (15) |

Recommended maximum service temperatures are based largely on General Electric experience with the several fluids, and in consideration of available physical and chemical property characteristics. Values for the hypothetical 500° F ester are, of course, assumed.

Maximum service temperature may be limited by either hydrolytic, oxidative, or thermal stability criteria. In a hydraulic system in contact with air, hydrolytic stability is limiting. In a lubrication system in contact with air, oxidative stability is limiting in all cases except for the perfluorinated fluid. In inerter systems, the thermal stability is limiting. (Volatility, lubricity, or fire safety may become limiting, however.) The limiting temperatures for the four study lubricants were assumed to be as listed in Table VIII.

Table VIII. FLITE Program Lubricants - Limiting Temperatures

| | Maximum Temperature, ° F | | |
|---|---|---|---|
| Lubricant | Thermal | Oxidative | Hydrolytic |
| MIL-L-27502 | 600 | 425 | 400 |
| 500° F Hypothetical Ester | 600 | 500 | 425 |
| Polyphenyl Ether | 800 | 600 | No Limit |
| Perfluorinated Polyether | 670 | No Limit | No Limit |

Equations for viscosity were developed for each of the study lubricants based on the design curves issued. No one simple mathematical equation can be fitted to such wide-range viscosity data. Viscosities of non-ester fluids deviate significantly from the curve fit used for hydrocarbons. Using two equations, however, an excellent fit over the entire range was achieved. A model reported in Reference 12 was used successfully, except that temperatur in degrees Rankine was utilized. This avoids logarithms of zero or negative numbers and division by zero. In the computer model, the switch from one equation to the other is made at 7.5 centistokes or an appropriate temperature. Equations for each lubricant are as follows ($\nu$ = kinematic viscosity in centistokes, and T = temperature in degrees Rankine):

<u>MIL-L-27502 and 500° F Hypothetical Ester</u>

$$\ln \ln (\nu + 0.6) = A + B \ln T \qquad (8)$$

(-40° to 500° F) $A = 24.3051$
$B = -3.64686$

<u>5P4E Polyphenyl Ether</u>

$$\ln \nu = A + B \ln T + C/T \qquad (9)$$

(100° to 250° F): $A = -528.076$
$B = 69.2459$
$C = 53595.4$

(250° to 700° F): $A = -47.0343$
$B = 5.47088$
$C = 9295.84$

<u>Perfluorinated Polyether</u>

$$\ln \nu = A + B \ln T + C/T \qquad (10)$$

(100° to 300° F): $A = -154.682$
$B = 19.6482$
$C = 20129.8$

(300° to 700° F): $A = -12.8457$
$B = 1.04858$
$C = 6117.77$

Linear equations were fitted to the specific heat data.

$$C_p = A + BT \qquad (11)$$

Temperature, T, is either in ° F or ° R; $C_p$ is either in Btu/lb/° F (or ° R) or Cal/gm/° K. Different values of A are used for Fahrenheit and Rankine and are presented in Table IX.

Table IX. Lubricant Viscosity Equation Coefficients

| | A (° F) | A (° R) | B | Range |
|---|---|---|---|---|
| MIL-L-27502 | 0.421546 | 0.278356 | $3.11486 \times 10^{-4}$ | (-40° to 500° F) |
| 500° F Ester | 0.421546 | 0.278356 | $3.11486 \times 10^{-4}$ | (-40° to 500° F) |
| Polyphenyl Ether | 0.336850 | 0.190436 | $3.185 \times 10^{-4}$ | (+100° to 700° F) |
| Perfluorinated Fluid | 0.203400 | 0.098588 | $2.280 \times 10^{-4}$ | (+100° to 700° F) |

# SECTION IV

# MISSION A RESULTS

## A. Utilization of Fuel Heat Sink

In addition to using the fuel as a heat sink for cooling the lubricants and hydraulic fluids, studies were made to determine the potential use of excess fuel heat sink for cooling turbine and exhaust system components in the GE16/FLITE-1A engine. The available fuel heat sink was considered to be the difference between the maximum permissible fuel temperatures of 325° F for JP-5/8 and 570° F for JP-7 and the fuel temperature at the exit of the main engine control. The objective of these studies was to define a heat exchanger system which could utilize the excess fuel heat sink in a practical engine cooling system. Screening studies were made of system concepts in terms of heat exchanger location, thermal environment, available fuel heat sink, and heat exchanger performance.

The heat exchanger design point was selected to be compatible with engine operation at cruise. The point was determined from an analysis of engine operating points along the Mission A flight path which showed that the engine cycle temperatures achieve their maximums and the permissible fuel temperature rise becomes minimum during the cruise portions of the mission. The average and maximum fuel temperatures supplied to the heat exchanger inlet during supersonic cruise are approximately 275° F and 300° F, respectively. The permissible fuel temperature rise at the cruise condition is shown in Table X.

Table X. Mission A Available Fuel Temperature Rise at Supersonic Cruise.

| Study | Fuel | $T_{Fuel}$ Interface (° F) | $T_{H-X\ in}$ (° F) | $T_{Allow}$ (° F) | $\Delta T_{Avail}$ (° F) |
|---|---|---|---|---|---|
| Base | JP-5 | 200 | 250 | 325 | 75 |
| 1 | JP-5/8 | 250 | 300 | 325 | 25 |
| 2 | JP-7 | 250 | 300 | 570[1] | 270 |

1 - Use of 570° F as the allowable JP-7 fuel temperature is based on a fuel wall temperature criteria of 725° F and the assumption that an approximate 100-150° F ΔT exists between the fuel and its wall temperature.

A number of GE16/FLITE-1A heat exchanger arrangements was qualitatively studied to determine which systems made effective use of the available fuel heat sink and which systems were compatible with practical engine designs. The system arrangements studied included the following:

1. Fuel/air heat exchanger for cooling the low pressure turbine cooling air.

2. Fuel/air heat exchanger for cooling the duct nozzle cooling air.

3. Fuel/air heat exchanger for a partical core air precooler.

4. Direct fuel cooling of the high pressure turbine diaphragm.

As the high pressure turbine cooling air circuit is within the rotating structure of the GE16/FLITE-1A engine, this cooling air was inaccessible for use in the heat exchanger study concepts.

When the candidate concepts were limited to fuel temperature increases of 25° F in Study 1 and 270° F in Study 2, Concepts 3 and 4 were eliminated as contenders due to insufficient fuel heat sink. The partial core air precooler (Concept 3) was considered impractical because with the fuel heat sink available, this system produced a flow path blockage and required a compensating increase in core size. There was sufficient fuel heat sink for the direct fuel cooling of the high pressure turbine diaphragm (Concept 4) since this concept required about 2-1/2 times the fuel heat sink made available when JP-7 is limited to a 270° F fuel temperature rise. Thus of the four concepts considered for the utilization of fuel heat sink in the mission, only the LP turbine cooling air cooler and the duct nozzle cooling air cooler were judged worthy of more detailed study.

For Study 1, which specifies JP-5/8 fuel at a maximum engine inlet fuel temperature of 250° F, thermal analysis results indicated end-of-cruise fuel temperatures of approximately 300 to 310° F at the fuel nozzles of the duct main burner and core combustor. Since JP-5 and JP-8 were considered to have a thermal stability limit of 325° F, each of these fuels had insufficient fuel heat sink capacity to justify the inclusion of a fuel/air heat exchanger for cooling either the low pressure turbine cooling air or the duct nozzle cooling air.

Two sets of JP-7 maximum fuel temperaure and maximum wall temperature criteria were considered for Study 2 (JP-7 @ 250° F).

- $T_{Fuel\ Max.}$ = 550° F and/or $T_{Wall\ Max.}$ = 575° F, which are considered to be zero risk levels leading to unrestricted fuel residence times without fuel decomposition or fuel side depositions.

- $T_{Fuel\ Max.}$ = 700° F and/or $T_{Wall\ Max.}$ = 725° F, which are considered to be limited risk temperature levels leading to shorter fuel residence time, some fuel side deposits, and a requirement to periodically clean the fuel side of the heat exchanger surfaces.

Each set of fuel temperature/wall temperature criteria shown above was used to define a cooling system which fully utilized the available fuel heat sink. The lower fuel temperature limit (550° F) was applied to the duct nozzle cooling air cooler design. Since the exhaust nozzle uses fan air (764° F at cruise) for cooling, it follows that the fuel tube wall temperature cannot reach the

725° F level associated with a limited risk system. Similarly, the low pressure turbine cooling air cooler operates with an air side inlet temperature of 1070° F which implies severe limitations on the cooling potential with a 550° F fuel temperature limit. Thus, the low pressure turbine cooling air cooler system is more practical when based on the use of the higher (725° F) wall temperature limit.

Fuel-to-air heat exchanger sizing the performance evaluations for the two heat exchanger systems were made. Each system utilized the total engine fuel flow in a heat exchanger which was located upstream of the engine control. The exchanger sizing point selected for each system study corresponded to the cruise operating condition and represented the maximum turbine inlet and cooling temperature operation for the engine.

Results of the heat exchanger system studies are presented in Tables XI through XVII. Table XII summarizes the design configurations and dimensional data for the two heat exchanger designs investigated for the LP turbine cooling air cooler. The corresponding performance data at the design point and four off-design operating points are summarized in Tables XIII and XIV. Similar results for the duct nozzle cooling air cooler are given in Tables XVI and XVII.

System 1 - (LP Turbine Cooling Air Cooler)

The low pressure turbine cooling air is Stage 3 bleed air and for this system is equal to 10.5% of the core flow ($W_{25}$). Since the baseline engine uses 15.5% $W_{25}$ for low pressure turbine cooling air, the addition of the fuel/air heat exchanger to the cooling circuit reduces the required coolant flow by about 32 percent. Some pertinent engine operating parameters corresponding to the heat exchanger design point and to typical operating points at which the heat exchanger performance was evaluated, are shown in Table XI.

The heat exchanger configuration selected is a bare tube cross flow heat exchanger with the fuel flow inside the tubes and the airflow normal to the tubes. This type of configuration generally results in minimum heat exchanger weight and is particularly well suited for aircraft engine applications, since it readily lends itself for uniform arrangement around the engine circumference within the engine outer casing. The heat exchanger required to meet the specified operating conditions consists of a bank of tubes of 0.187 inch OD, 0.007 inch wall thickness located in the interstage bleed air annular duct above the combustor as shown in Figure 39. The tubes are arranged circumferentially in a 5 x 40 array. Fuel is fed to the tubes from a single axial manifold and is discharged from the tubes into a second axial manifold located 180° from the inlet. The manifolds are spaced 180° apart and are split longitudinally, permitting a simple assembly of the heat exchanger. The configuration includes orifices at the tube exit in order to assure uniform flow distribution. The orifice pressure drops are equal to 3 times the tubing pressure drop. Radial supports located 3.75 inches apart minimize bending stresses on the tubing and assure natural frequencies above engine and vortex shedding excitation frequencies. A schematic diagram of the heat exchanger configuration is shown in Figure 40. The heat exchanger material is a high strength stainless steel alloy. Estimated weight of the heat exchanger, exclusive of the fuel supply

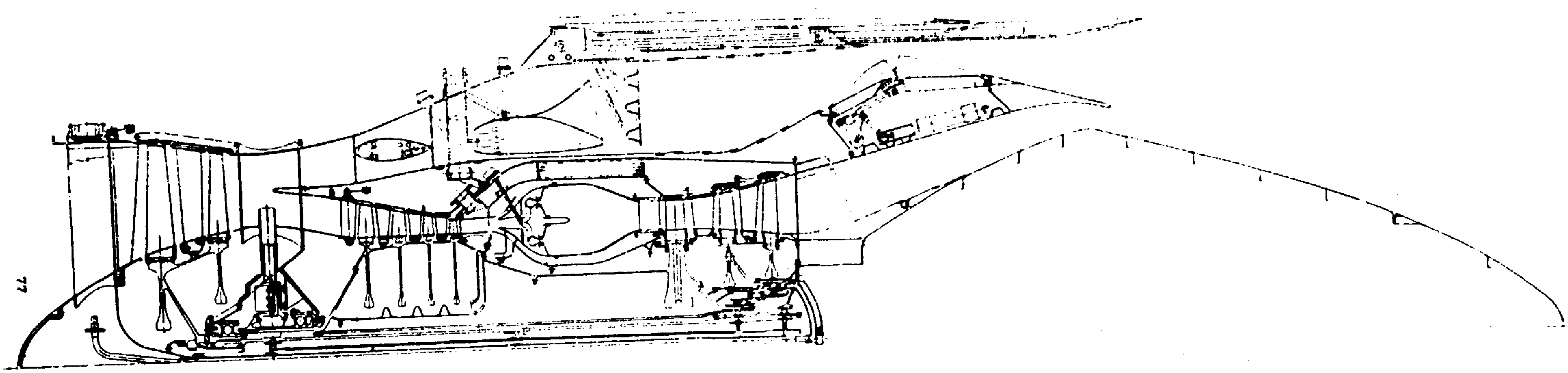


Figure 39. GE16/FLITE-1C Engine Cross Section.

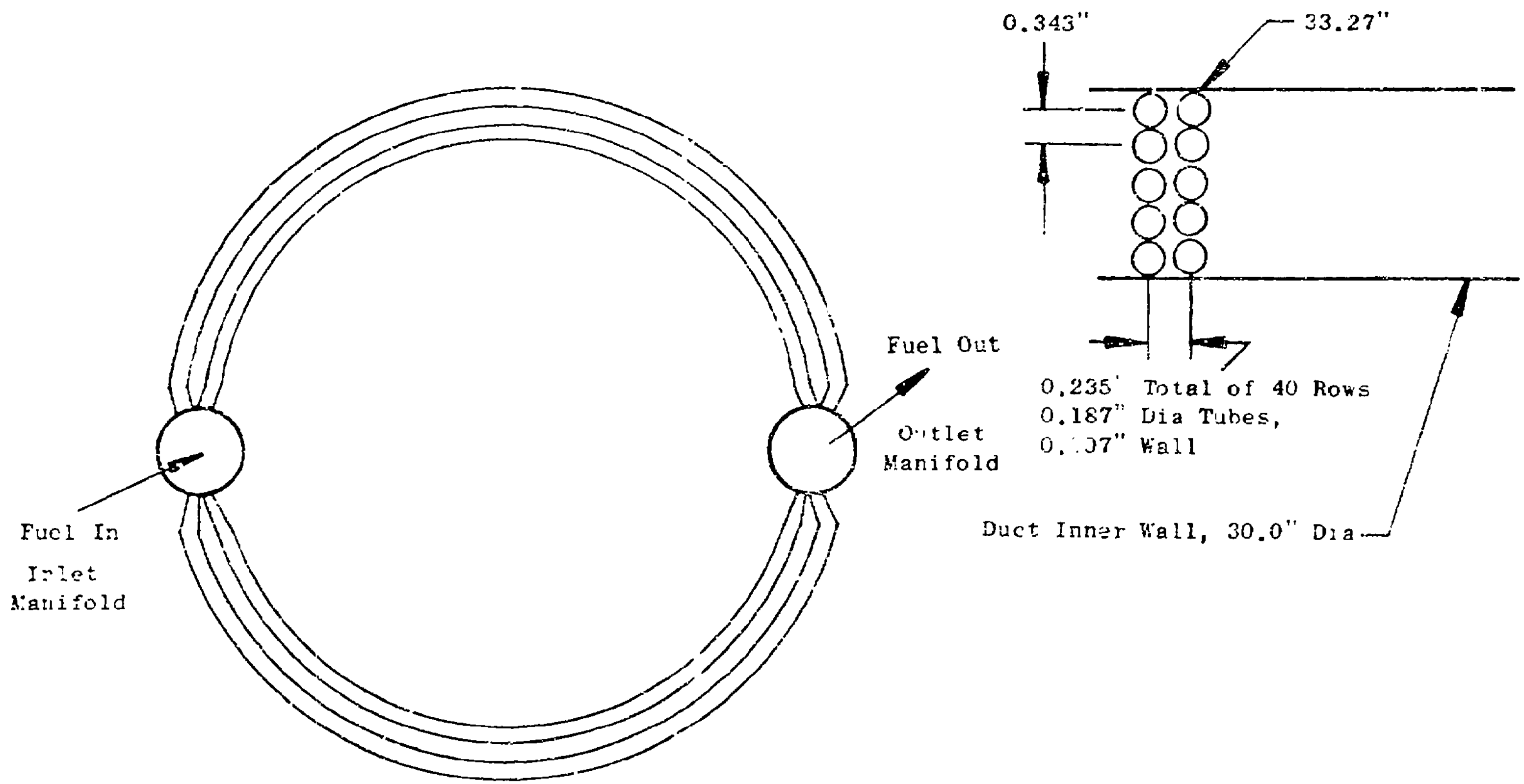



Figure 40. Schematic Diagram of Heat Exchanger Configuration for LP Turbine Cooling Air Heat Exchanger.

lines is 40.4 lb, of which 23.7 lb is tubing weight and the balance is the weight of the manifolds and support structure. Titanium fuel lines from the hydraulic oil heat exchanger to the fuel/air exchanger and return to the control pod weigh 4.84 lb making the total estimated system weight equal to 47.4 lb for the 100% engine size. A tabulation of the basic heat exchanger dimensions is given in Table XII.

The resulting heat exchanger performance obtained for the above configuration is shown in Table XIII. In addition to design point data, performance data at four selected off-design operating points are also included in Table XIII. It may be observed that this heat exchanger configuration yields a cooling air temperature decrease of 503° F with a corresponding fuel temperature rise of 267° F. The maximum fuel and tube wall temperatures are obtained at the end-of-cr[illegible] operating point at which time the maximum temperatures are 567° F and [illegible] for the fuel and tube wall, respectively. The maximum air side pressure drop is 1.80% and occurs at the design point.

An alternate heat exchanger configuration for the low pressure turbine cooling air designed to further reduce the fuel wall temperatures, was also evaluated. The configuration was obtained by modifying the original configuration so as to introduce four passes into the heat exchanger fuel flow circuit. This can be realized by the addition of two baffles, each, into the inlet and exit manifolds. The design configuration and the dimensional data for the LP turbine cooling air four-pass cross-flow heat exchanger is given in Table XII and the corresponding performance data in Table XIV. It may be observed the maximum fuel surface temperature is reduced from 717° F to 600° F. This is accomplished at the expense of increased fuel side pressure drop, however, the resulting pressure drops are still within acceptable limits

<u>System 2 (Duct Exhaust Nozzle Cooling Air Heat Exchanger)</u>

The heat exchanger sizing point selected for this study corresponds to the cruise operating condition of the aircraft flight mission and represents the maximum $T_{41}$ and coolant temperature operation of the flight spectrum for the engine. The average fuel temperature available at the heat exchanger inlet is approximately 275° F. The JP-7 fuel temperature rise for the fuel to exhaust nozzle cooling air was set at 300° F. The nozzle cooling air is equal to [illegible] 0% of the fan flow ($W_1$). Some pertinent engine operating parameters, corresponding to the heat exchanger design point and to typical operating points at which the heat exchanger performance was evaluated are shown in Table XV.

Table XI. Operating Conditions for LP Turbine Cooling Air Heat Exchanger.

| Operating Point | Cruise Des. Pt | End of Cruise | Takeoff | End of Accel | Combat |
|---|---|---|---|---|---|
| $T_4$ (°F) | 3,702 | 3,702 | 3,559 | 3,491 | 3,646 |
| Core Airflow $W_{25}$ (pps) | 23.4 | 23.4 | 121.8 | 177.65 | 32.0 |
| Coolant Flow (pps) | 2.44 | 2.44 | 12.65 | 18.5 | 3.35 |
| Duct Fuel Flow (pps) | 1.0 | 1.0 | 9.15 | 20.03 | 4.0 |
| Core Fuel Flow (pps) | 0.78 | 0.78 | 4.45 | 5.20 | 1.03 |
| Total Fuel Flow (pps) | 1.78 | 1.78 | 13.60 | 25.50 | 5.03 |
| $P_3$ (psia) | 33.97 | 33.97 | 166.7 | 246.6 | 45.85 |
| $T_3$ (° F) | 1,173 | 1,173 | 663 | 1,153 | 1,165 |
| Coolant Pressure (psia) (1) | 27.3 | 27.3 | 118.0 | 195.0 | 37.0 |
| Coolant Inlet Temperature (° R) (1) | 1,530 | 1,530 | 970 | 1,508 | 1,524 |
| Fuel Inlet Temperature (°R) | 735 | 735 | 619 | 660 | 685 |

(1) Stage 3 bleed

Table XII. LP Turbine Cooling Air Cooler Heat Exchanger Configurations, 100% Engine Size.

| | 1 - Pass H-X Config. | 4-Pass H-X Config. |
|---|---|---|
| Tube OD (in) | 0.187 | 0.187 |
| Tube Wall Thickness (in) | 0.007 | 0.007 |
| Transverse Spacing (in) | 0.327 | 0.319 |
| Axial Spacing (in) | 0.235 | 0.235 |
| Heat Exchanger Axial Length (in) | 9.588 | 10.15 |
| Number of Transverse Rows | 5 | 5 |
| Number of Axial Rows | 40 | 40 |
| Number of Manifolds | 2 | 4 |
| Manifold Diameter, ID (in) | 3.0 | 3.88 |
| Annular Passage ID (in) | 30.0 | 30.0 |
| Annular Passage OD (in) | 33.27 | 33.19 |
| Total External Heat Transfer Area ($ft^2$) | 81.3 | 81.2 |
| Heat Exchanger Volume ($in^3$) | 1,559.8 | 1,606.9 |
| Tubing Weight (lb) | 23.74 | 23.71 |
| Manifold Weight (lb) | 6.60 | 7.80 |
| Support Weight (lb) | 4.00 | 4.60 |
| H-X Weight (lb) | 34.34 | 36.11 |
| Fuel Piping Weight (lb) | 6.01 | 6.01 |
| Total System Weight (lb) | 40.35 | 42.12 |

Table XIII. Operating Conditions for LP Turbine Cooling Air Heat exchanger (Single-Pass Cross-Flow Configuration), 100% Engine Size.

| Operating Point | Cruise Des. Pt. | End of Cruise | T/O | End of Accel | Combat |
|---|---|---|---|---|---|
| Core Airflow, $W_{25}$ (pps) | 23.4 | 23.4 | 121.6 | 177.6 | 32.0 |
| LP Turbine Coolant Flow (pps) | 2.44 | 2.44 | 12.6 | 18.5 | 3.35 |
| Duct Fuel Flow (pps) | 1.0 | 1.0 | 9.15 | 20.30 | 4.0 |
| Core Fuel Flow (pps) | 0.78 | 0.78 | 4.45 | 5.20 | 1.03 |
| Total Fuel Flow (pps) | 1.78 | 1.78 | 13.60 | 25.50 | 5.03 |
| $P_3$ (psia) | 33.97 | 33.97 | 166.7 | 246.6 | 45.85 |
| $T_3$ (° R) | 1,633 | 1,633 | 1,123 | 1,613 | 1,625 |
| Coolant Pressure (psia)* | 27.3 | 27.3 | 118.0 | 195.0 | 37.0 |
| Coolant Inlet Temp. (° R)* | 1,530 | 1,530 | 970 | 1,508 | 1,524 |
| Fuel Inlet Temp. (° R) | 735 | 785 | 619 | 660 | 685 |
| $\Delta T$ Fuel (° F) | 266.6 | 242.4 | 76.2 | 146.3 | 162.1 |
| $\Delta T$ Air (° F) | 503.2 | 480.7 | 173.7 | 438.7 | 555.4 |
| $(\Delta P/P)$ Air (%) | 1.78 | 1.80 | 1.42 | 1.56 | 1.61 |
| $\Delta P$ Fuel (psia) | 0.04 | 0.04 | 11.20 | 3.20 | 0.20 |
| Effectiveness (%) | 0.633 | 0.645 | 0.495 | 0.516 | 0.702 |
| $T_{Fuel}$ Max. (° F) | 541.6 | 567.4 | 235.2 | 346.3 | 387.1 |
| $T_{Wall}$ Max. (° F) | 706.4 | 716.5 | 314.4 | 507.3 | 513.7 |

* Stage 3 Bleed

Table XIV. Operating Conditions for LP Turbine Cooling Air Heat Exchanger (Four-Pass Cross-Flow Configuration), 100% Engine Size.

| Operating Point | Cruise Des. Pt. | End of Cruise | T/O | End of Accel | Combat |
|---|---|---|---|---|---|
| Core Airflow, $W_{25}$ (pps) | 23.4 | 23.4 | 121.8 | 177.6 | 32.0 |
| LP Turbine Coolant Flow (pps) | 2.44 | 2.44 | 12.6 | 18.5 | 3.35 |
| Duct Fuel Flow (pps) | 1.0 | 1.0 | 9.15 | 20.30 | 4.0 |
| Core Fuel Flow (pps) | 0.78 | 0.78 | 4.45 | 5.20 | 1.03 |
| Total Fuel Flow (pps) | 1.78 | 1.78 | 13.60 | 25.50 | 5.03 |
| $P_3$ (psia) | 33.97 | 33.97 | 166.7 | 246.6 | 45.85 |
| $T_3$ (° R) | 1,633 | 1,633 | 1,123 | 1,613 | 1,625 |
| Coolant Pressure (psia)* | 27.3 | 27.3 | 118.0 | 195.0 | 37.0 |
| Coolant Inlet Temp. (° R)* | 1,530 | 1,530 | 970 | 1,508 | 1,524 |
| Fuel Inlet Temp. (° R) | 735 | 785 | 619 | 660 | 685 |
| $\Delta T$ Fuel (° F) | 265.2 | 240.5 | 84.9 | 159.8 | 164.1 |
| $\Delta T$ Air (° F) | 499.9 | 476.2 | 195.0 | 483.4 | 563.9 |
| $(\Delta P/P)$ Air (%) | 1.94 | 1.97 | 1.60 | 1.72 | 1.73 |
| $\Delta P$ Fuel (psia) | 0.35 | 0.35 | 14.8 | 47.5 | 2.30 |
| Effectiveness (%) | 0.629 | 0.639 | 0.556 | 0.570 | 0.719 |
| $T_{fuel}$ Max. (° F) | 540.2 | 565.5 | 243.9 | 359.8 | 289.1 |
| $T_{Wall}$ Max. (° F) | 581 | 600 | 257 | 287 | 413 |
| Residence Time (sec) | 6.15 | 6.00 | 0.96 | 0.46 | 2.39 |

* Stage 3 Bleed

Table XV. Operating Conditions for Duct Nozzle Cooling Air Heat Exchanger, 100% Engine Size.

| Operating Point | Cruise Des. Pt | End of Cruise | Takeoff | End of Accel | Combat |
|---|---|---|---|---|---|
| Fan Air Flow Rate, $W_1$ (pps) | 72.96 | 72.96 | 287.4 | 510.6 | 97.69 |
| Coolant Flow Rate (pps) | 2.30 | 2.30 | 8.65 | 16.3 | 3.08 |
| Duct Fuel Flow Rate (pps) | 1.0 | 1.0 | 9.15 | 20.30 | 4.0 |
| Core Engine Fuel Flow Rate (pps) | 0.78 | 0.78 | 4.45 | 5.20 | 1.03 |
| Total Fuel Flow Rate (pps) | 1.78 | 1.78 | 13.60 | 25.50 | 5.03 |
| Coolant Pressure, $P_{14}$ (psia) | 13.46 | 13.46 | 33.46 | 96.46 | 17.91 |
| Coolant Inlet Temperature, $T_{14}$, (° F) | 764 | 764 | 223 | 746 | 756 |
| Fuel Inlet Temperature (° F) | 275 | 325 | 159 | 200 | 225 |

The heat exchanger was assumed to be located between the inner duct wall and the compressor casing with the fuel circuit being upstream of the main engine control. Thus, splitting and metering of the core engine and duct fuel flow takes place downstream of the heat exchanger. This approach simplified the heat exchanger design and is believed to be particularly justified on the basis of the low fuel temperature rise limit set for this study and anticipated relaxation in control component temperature limits that may result from future advancements in technology.

The basic heat exchanger configuration is a single-pass cross-flow design similar to the single pass LP turbine configuration. Details of the design are given in Table XVI and the resulting performance is given in Table XVII.

Evaluation of the duct nozzle cooling air fuel/air heat exchanger indicated the following results.

- o The duct nozzle cooling air supply temperature is reduced 297° F and the cooling airflow is reduced 29 percent at the design point.

- o The maximum fuel tube wall temperature is 554° F which occurs at the end of cruise. Since the duct nozzle uses fan air (764° F at cruise) for cooling, it follows that the fuel tube wall temperatures cannot reach the design criteria at 725° F. Thus the usable fuel heat sink is restricted to approximately 60 percent of the available fuel heat sink in the duct nozzle cooling air cooler.

Table XVI. Exhaust Nozzle Cooling Air Heat Exchanger Design Summary, 100% Engine Size.

| | Single Pass H-X. Configuration |
|---|---|
| Tube OD (in) | 0.188 |
| Tube Wall Thickness (in) | 0.007 |
| Transverse Spacing (in) | 0.343 |
| Axial Spacing (in) | 0.235 |
| Heat Exchanger Axial Length (in) | 9.588 |
| Number of Transverse Rows | - |
| Number of Axial Rows | 40 |
| Number of Manifolds | 2 |
| Manifold Diameter, ID (in) | 2.0 |
| Annular Passage ID (in) | 27.0 |
| Annular Passage OD (in) | 30.43 |
| Total External Heat Transfer Area ($ft^2$) | 73.8 |
| Heat Exchanger Volume ($in^3$) | 1483.5 |
| Tubing Weight (lb) | 21.56 |
| Manifold Weight (lb) | 5.06 |
| Support Weight (lb) | 3.81 |
| H-X Weight (lb) | 30.43 |
| Fuel Piping Weight (lb) | 4.92 |
| Total System Weight (lb) | 35.35 |

Table XVII. Operating Conditions for Duct Nozzle Cooling Air Heat Exchanger.

| Operating Point | Cruise Des. Pt. | End of Cruise | T/O | End of Ac. | Combat |
|---|---|---|---|---|---|
| Fan Air Flow, $W_1$ (pps) | 72.96 | 72.96 | 274.0 | 510.6 | 97.69 |
| Duct Nozzle Coolant (pps) | 2.3 | 2.3 | 8.65 | 16.3 | 3.08 |
| Duct Fuel Nozzle (pps) | 1.0 | 1.0 | 9.15 | 20.30 | 4.0 |
| Core Fuel Flow (pps) | 0.78 | 0.78 | 4.45 | 5.20 | 1.03 |
| Total Fuel Flow (pps) | 1.78 | 1.78 | 13.60 | 25.50 | 5.03 |
| Coolant Press., $P_{14}$ (psia) | 13.46 | 13.46 | 23.46 | 96.46 | 17.91 |
| Coolant Inlet Temp. (° R) | 1,224 | 1,224 | 683 | 1,206 | 1,216 |
| Fuel Inlet Temp. (° R) | 735 | 785 | 619 | 660 | 685 |
| $\Delta T$ Fuel (° F) | 156.2 | 136.3 | 10.3 | 81.3 | 99.3 |
| $\Delta T$ Air (° F) | 296.6 | 271.8 | 34.4 | 273.4 | 365.6 |
| $(\Delta P/P)$ Air (%) | 5.05 | 5.13 | 6.04 | 3.77 | 4.61 |
| $\Delta P$ Fuel (psid) | 0.04 | 0.04 | 1.08 | 3.32 | 0.16 |
| Effectiveness | 0.607 | 0.619 | 0.528 | 0.501 | 0.689 |
| $T_{fuel}$ Max. (° F) | 431.2 | 461.3 | 169.3 | 281.3 | 324.7 |
| $T_{wall}$ Max. (° F) | 538.3 | 553.87 | 181.6 | 382.2 | 411.9 |

- o No increase in casing diameter is required for the duct nozzle cooling air cooler.

- o The air-side pressure drop reaches 6.04 percent at takeoff and represents a potential problem due to the fact that a portion of the air passing through the heat exchanger is used for inner liner cool' · in the duct burner.

- o Fuel residence time in the heat exchanger ranges from a low of 0.52 seconds at the end of accel to a high of 7.45 seconds at the end of a cruise.

- o The system volume heat transfer surface area and weight are 1,483 cubic inches, 73.8 square feet, and 44.74 pounds, respectively. This is based on 100 percent engine size.

Based on the heat exchanger results and performance for Study 2 (JP-7 fuel supplied at 250° F maximum to the aircraft/engine interface), the heat exchanger performance was determined using three engine concepts:

1. Baseline engine (GE16/FLITE 1A) - does not use fuel heat sink in turbine cooling circuits.

2. Baseline plus duct nozzle cooling air cooler - the fuel heat sink is used to reduce the cooling air quantity required by the duct burner exhaust nozzle. The fuel/air heat exchanger is located in the cavity between the fan duct inner wall and the compressor casing.

3. Baseline plus low pressure (LP) turbine cooling air cooler- the fuel heat sink is used to reduce the cooling air quantity required by the LP turbine vanes and blades. The fuel/air heat exchanger is located in the interstage bleed air duct above the core combustor.

The relative performance of the three concepts are shown in Table XVIII at various operating conditions. Based on these results, the following points are noted:

1. Based on the performance results shown in Table XV, the LP turbine cooling air cooler concept is superior to the duct nozzle cooling air cooler concept. At the engine sizing point the airflow size can be reduced by 1.5% through use of a LP turbine cooling air cooler.

2. The reduction in engine SFC with an LP turbine cooling air cooler averages 0.3% for the four operating conditions shown in Table XVIII.

Table XVIII. Relative Performance of GE16/FLITE-1A Baseline Engine at Several Operating Points (JP-7 Fuel), 100% Engine Size.

| | SLS | | Combat | | Start of Cruise | | End of Cruise | |
|---|---|---|---|---|---|---|---|---|
| Configuration | $\frac{F_N/W_1}{F_N/W_1 \text{ Base*}}$ | $\frac{SFC}{(SFC)_{Base}}$ | $\frac{F_N/W_1}{F_N/W_1 \text{ Base}}$ | $\frac{SFC}{(SFC)_{Base}}$ | $\frac{F_N/W_1}{F_N/W_1 \text{ Base}}$ | $\frac{SFC}{(SFC)_{Base}}$ | $\frac{F_N/W_1}{F_N/W_1 \text{ Base}}$ | $\frac{SFC}{(SFC)_{Base}}$ |
| Baseline* | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Duct Nozzle Cooling Air Cooler | 1.003 | 1.007 | 1.005 | 1.004 | 1.006 | 1.004 | 1.007 | 1.001 |
| LP Turbine Cooling Air Cooler | 1.025 | 0.997 | 1.015 | 0.99[illegible] | 1.016 | 0.996 | 1.027 | 0.999 |

* Base is GE16/FLITE-1A

## B. Thermal Analysis

### B.1 Study 1

Figure 41 shows the fluid system schematic for Study 1. This study permitted the maximum fuel temperature to the engine to be 250° F. An analysis of the heat sink requirements for the aircraft produced the aircraft/engine interface fuel temperature profile shown in Figure 42. The critical cooling region for the aircraft systems occurs during idle-descent where the fuel temperatures reach the 250° F maximum level. This phase of the mission is also where the maximum engine fuel temperatures are achieved. Coupling these results would produce severe overtemperature conditions in the fuel during idle-descent without effective countermeasures.

As with the baseline engine, this modification to the engine fuel delivery system involves the definition of a fuel recirculation system to provide additional heat sink during idle-descent. This system involves a modified main engine control to include a check valve, a solenoid-actuated shut-off valve, a fuel temperature sensor and logic tie-in that is initiated from power lever position and fuel temperature entering the control. A fixed orifice, sized for maximum recirculation fuel flow at the initiation of idle-descent, maintains 300° F maximum fuel temperature recirculating to the aircraft main feed tank.

The incorporation of the fuel recirculation system resulted in a weight penalty of 2.9 pounds in the engine fuel system, slight additional weight in the aircraft fuel system and produced about a [illegible]° F temperature rise in the main feed tank. The maximum recirculation flows and fuel weight increments required with each of the candidate lubricants are indicated in Table XIX.

Table XIX. Mission A/Study 1 Recirculation Fuel Flow Rates, 129.75% Engine Size.

| Lube/Hydraulic Fluid | Maximum Recirculation Fuel Flow (pph) | Fuel Weight Increment (lb) |
|---|---|---|
| MIL-L-27502 | 4,500 | 315 |
| 500° F Ester | 4,300 | 301 |
| Polyphenyl Ether | 4,150 | 291 |
| Perfluorinated Polyether | 4,000 | 280 |

The definition of the GE16/FLITE-1B fluid power system remained the same as that defined for the baseline. An investigation of the use of the four lubricants as hydraulic fluids produced the weight effects shown in Table XX.

In the GE16/FLITE-1B engine lubrication system, engine volumetric oil flow was allowed to remain the same for each lubricant. System optimization with the higher temperature lubricants was accomplished by the removal of heat shields and insulation and by scaling the aft sump cooling air fuel/air cooler.

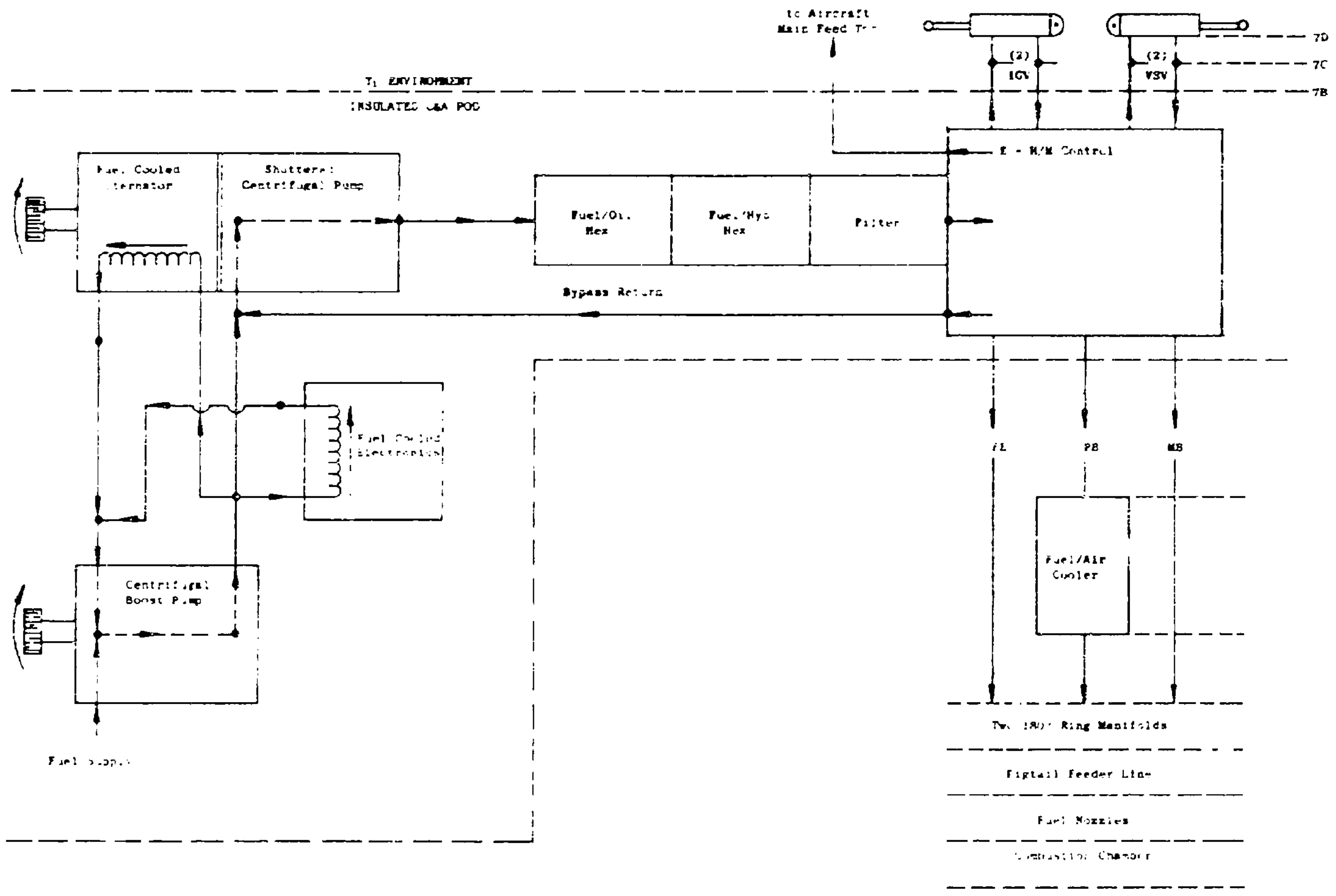



Figure 41. Mission A/Study 1 Fluid System Schematic.

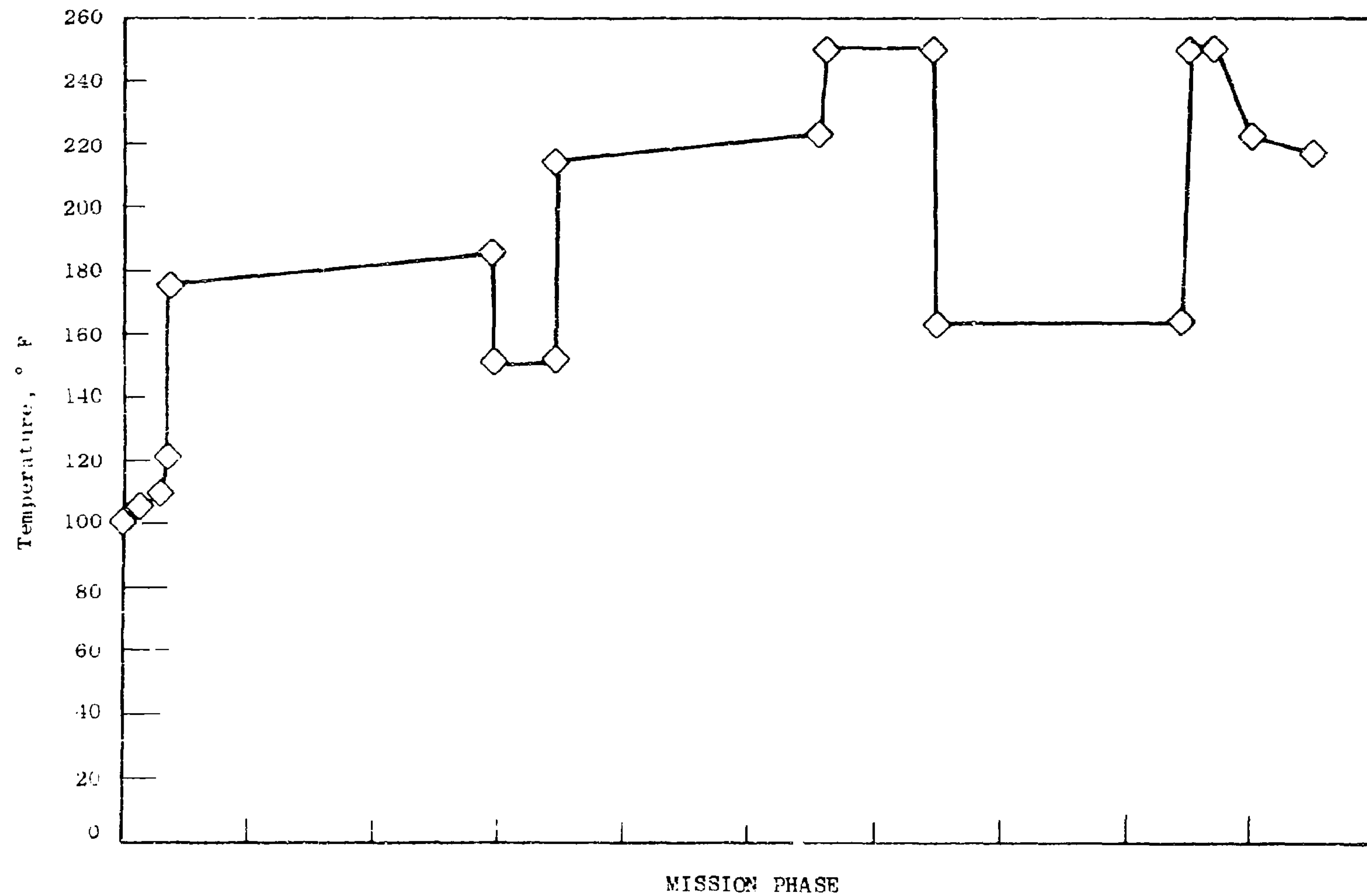



Figure 42. Mission A/Study 1 Engine Inlet Fuel Temperature Profile.

Table XX. GE16/FLITE-1B Baseline Weight Comparison-Fuel Delivery System, Fluid Power System.

| Fuel and Fluid Power System[1] Components | Fuel System ($\Delta$ Wt - lb) FLITE-1A Baseline JP-5 at 200° F | FLITE-1B JP-5/8 JP-5 at 250° F | Fluid Power System ($\Delta$ Wt - lb) MIL-L-27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|---|---|
| Computer ($T \leq 280°$ F) | 35 | 35 | --- | --- | --- | --- |
| Recirculating Fuel System | None | 2.9 | --- | --- | --- | --- |
| Insulation | 8.4 | 8.4 | 4.0 | 4.0 | 3.1 | 2.9 |
| FPS Fluid Weight (203 $in^3$ @ 80° F) | --- | --- | 7.19 | 7.19 | 8.81 | 13.98 |
| Integral Hyd Pump (Hiduminium $\leq 450°$ F) | --- | --- | 19.2 | 19.2 | 19.2 | 22.4 |
| 4-$A_{18}$ Actuators | --- | --- | 17.1 | 17.1 | 17.1 | 19.66 |
| $A_9$ Rot. Motor | --- | --- | 17.2 | 17.2 | 17.2 | 19.78 |
| Total Weight (lb) | 43.4 | 46.3 | 64.69 | 64.69 | 65.41 | 78.72 |
| Delta Weight | --- | +2.9 | --- | --- | +0.72 | +14.03 |

(1) Only components that change weight are listed

This cooler is located in the duct preburner fuel line where the fuel and air flows achieve the balance necessary for satisfactory heat exchanger performance. The cooler requirements for each of the four lubricants is shown in Table XXI. No cooling is required for the perfluorinated polyether nor is there sump air cooling required for any of the lubricants during idle descent. The elevated oxidative stability of the perfluorinated polyether permits the removal of the heat shield on the aft wall of the forward sump, however, its high vapor pressure necessitates nonvented sumps. In these sump designs, the carbon seals are used as air seals. New labyrinth oil seals are added with the intermediate cavities vented overboard to ambient pressure.

Lube system weight changes for the four lubricants are summarized in Table XXII. A summary of the total engine weight change for the four candidate lubricants is given in Table XXIII.

Figures 43 through 46 depict the results of flying the mission with each of the candidate lubricants. The fuel recirculation for each lubricant is maintained for the first five minutes of idle-descent. This recirculation permits operation of the system during idle-descent with the fuel delivery, fluid power and lubrication systems all operating within their respective thermal limits.

B.2 Study 2

Study 2 requires the use of JP-7 fuel at a maximum inlet temperature of 250° F with each of the candidate lubricants. This fuel change permits an increase in the maximum fuel temperatures to 700° F.

A schematic of the GE16/FLITE-1C system is shown in Figure 47. The system is essentially the same as the Mission A/Study 1 system with the exception that an additional fuel air cooler was added upstream of the fuel control to utilize the additional temperature capability of JP-7 fuel. This cooler accepts 15.6% of the compressor third stage bleed air and provides cooling air for the LP turbine. The fact that the heat exchanger can be located upstream of the control simplifies the heat exchanger design in that all splitting and metering of the core engine and duct fuel flow takes place downstream of the heat exchanger. The engine fuel control is a laminated plate, titanium-body design that permits the elevated fuel temperatures. Stainless steel piping and manifolds are required for the high temperature requirements.

The GE16/FLITE-1C fluid power system design remained essentially unchanged. For the polyphenyl ether and perfluorinated polyether lubricants, the design of the integral hydraulic pump was modified to include a stainless steel housing and stainless steel seals. Stainless steel piping was required to handle the higher temperature capability of the perfluorinated polyether.

The GE16/FLITE-1C engine lubrication system also remained essentially unchanged from the Study 1 design. Nonvented sump designs are still needed for the perfluorinated polyether lubricant to offset the deleterious effects of its high vapor pressure.

Table XXI. GE16/FLITE-1B Fuel/Air Cooler Requirements.

Design Flight Condition

$$WAIR = 0.00241 \times 1.24 \times 23.4 = 0.070 \text{ pps}$$

$$TBLD3 = T_{A_1} = 1{,}072° \text{ F}$$

| | A | B | C | D |
|---|---|---|---|---|
| Q (Btu/min) | 358 | 234 | 100 | 0 |
| $\Delta T_{air}$ (° F) | 329 | 214 | 91 | 0 |
| $T_{A_2}$ (° F) | 743 | 858 | 981 | 1072 |
| TASP (° F) | 828 | 920 | 1019 | 1092 |

A = MIL-L-27502

B = 500° F Ester

C = Polyphenyl Ether

D = Perfluorinated Polyether

$T_{A_1}$ = Cooler air inlet temperature

$T_{A_2}$ = Cooler air discharge temperature

TASP = Air temperature at sump (includes heat pickup in piping)

Table XXII. GE16/FLITE-1B Lube System Weight (Variable Items Only).

| Parameter | MIL-L 27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|
| Fuel/Air Cooler (lb) | 10.7 | 7.0 | 3.0 | 0 |
| Lube & Hydraulic Coolers (lb) | 14.7 | 9.4 | 7.0 | 5.6 |
| "A" Sump Aft Wall Heat Shields (lb) | 1.2 | 1.2 | 1.2 | 0 |
| Fluid Weight (Tank Fill Volume + 1.0 gal. "lost" oil @ 80° F fill Temp.) (lb) | 20.6 | 24.0 | 28.6 | 39.6 |
| Lub/Hydraulic Tank (lb) | 17.4 | 18.4 | 18.1 | 17.4 |
| Additional Hardware for Nonvented "A" Sump (lb) | 0 | 0 | 0 | 11.8 |
| Additional Hardware for Nonvented "B" Sump (lb) | 0 | 0 | 0 | 7.9 |
| Total (variable items) (lb) | 64.6 | 60.0 | 57.9 | 82.3 |
| Δ Weight (lb) | --- | -4.6 | -6.7 | +17.7 |

Table XXIII. Summary of GE16/FLITE-1B Engine Weight Changes for the Candidate Lubricants, 129.75% Engine Size.

| | FLITE-1B JP-5@250° F | MIL-L 27502 | Hypothetical Ester | Polyphenyl Ester | Perfluorinated Polyether |
|---|---|---|---|---|---|
| Fuel System (lb) | 0 | 0 | 0 | 0 | 0 |
| Fluid Power (lb) System | --- | 0 | 0 | +1.62 | +15.13 |
| Lube System (lb) | --- | 0 | -4.6 | -6.7 | +17.7 |
| Engine Cycle (lb) | 0 | --- | --- | --- | --- |
| Total Δ Weight (lb) | 0 | 0 | -4.6 | -5.1 | +32.8 |

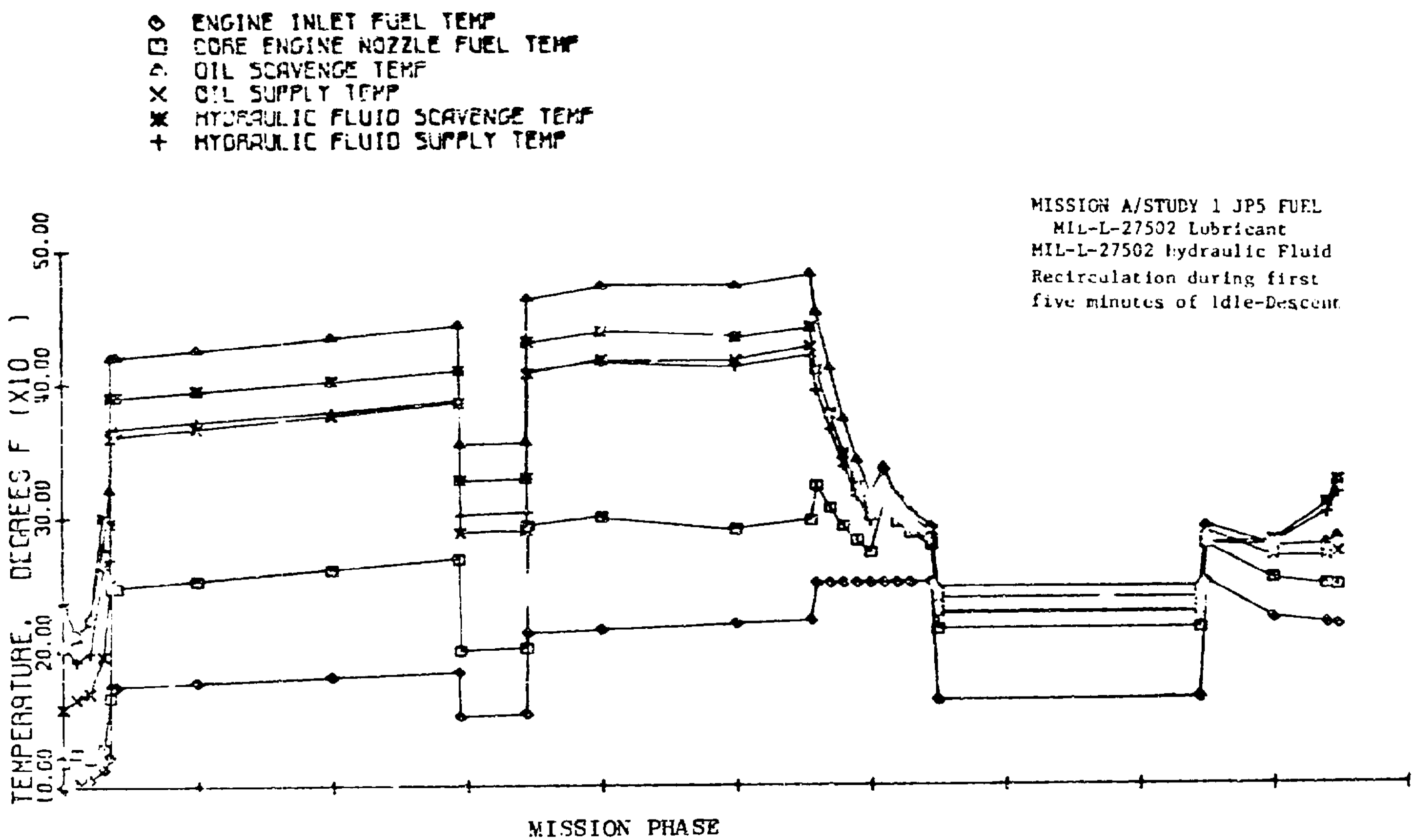



Figure 43. GE16/FLITE-1B Thermal Profiles, MIL-L-27502.

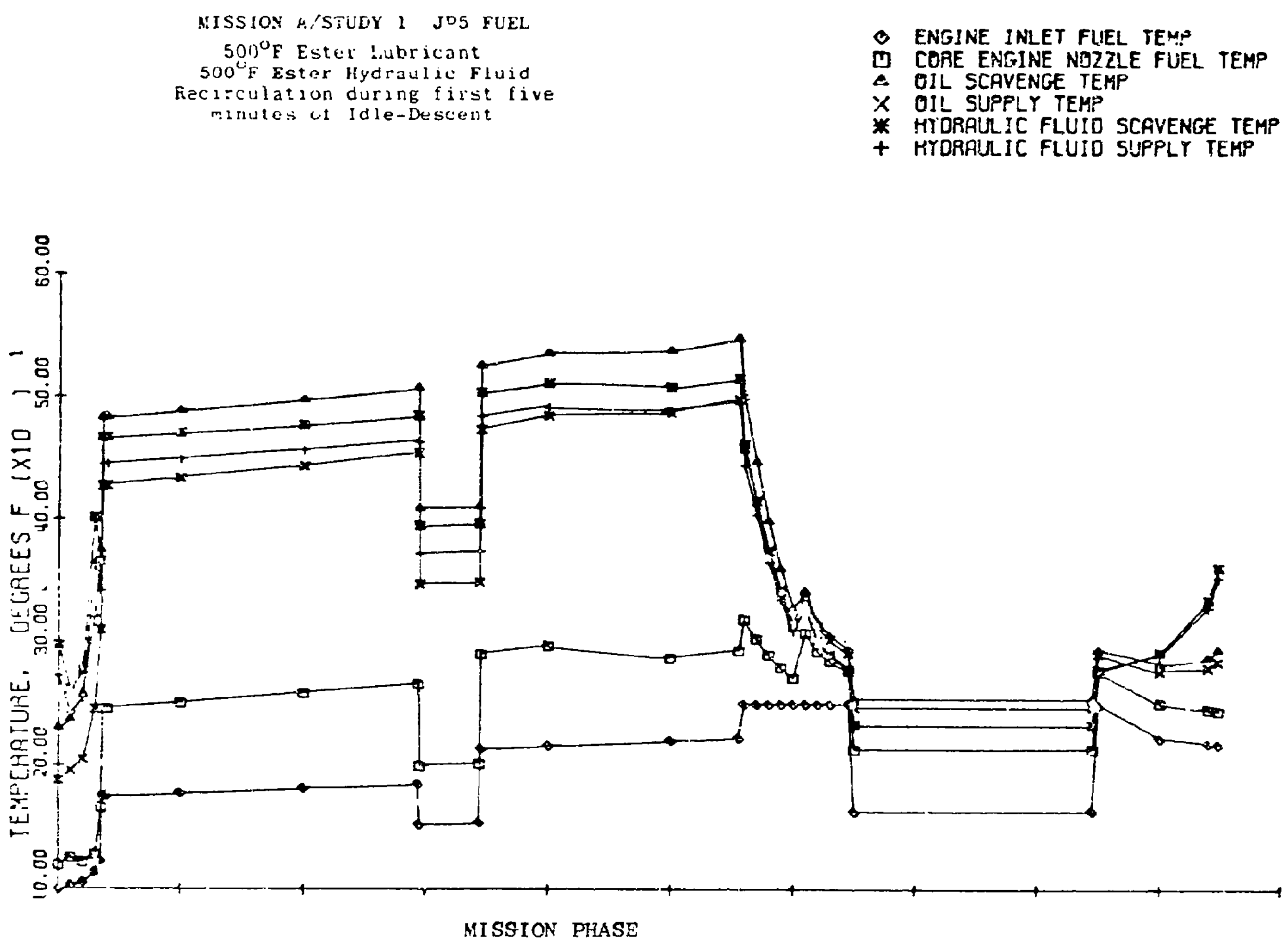



Figure 44. GE16/FLITE-1B Thermal Profiles, 500° F Ester.

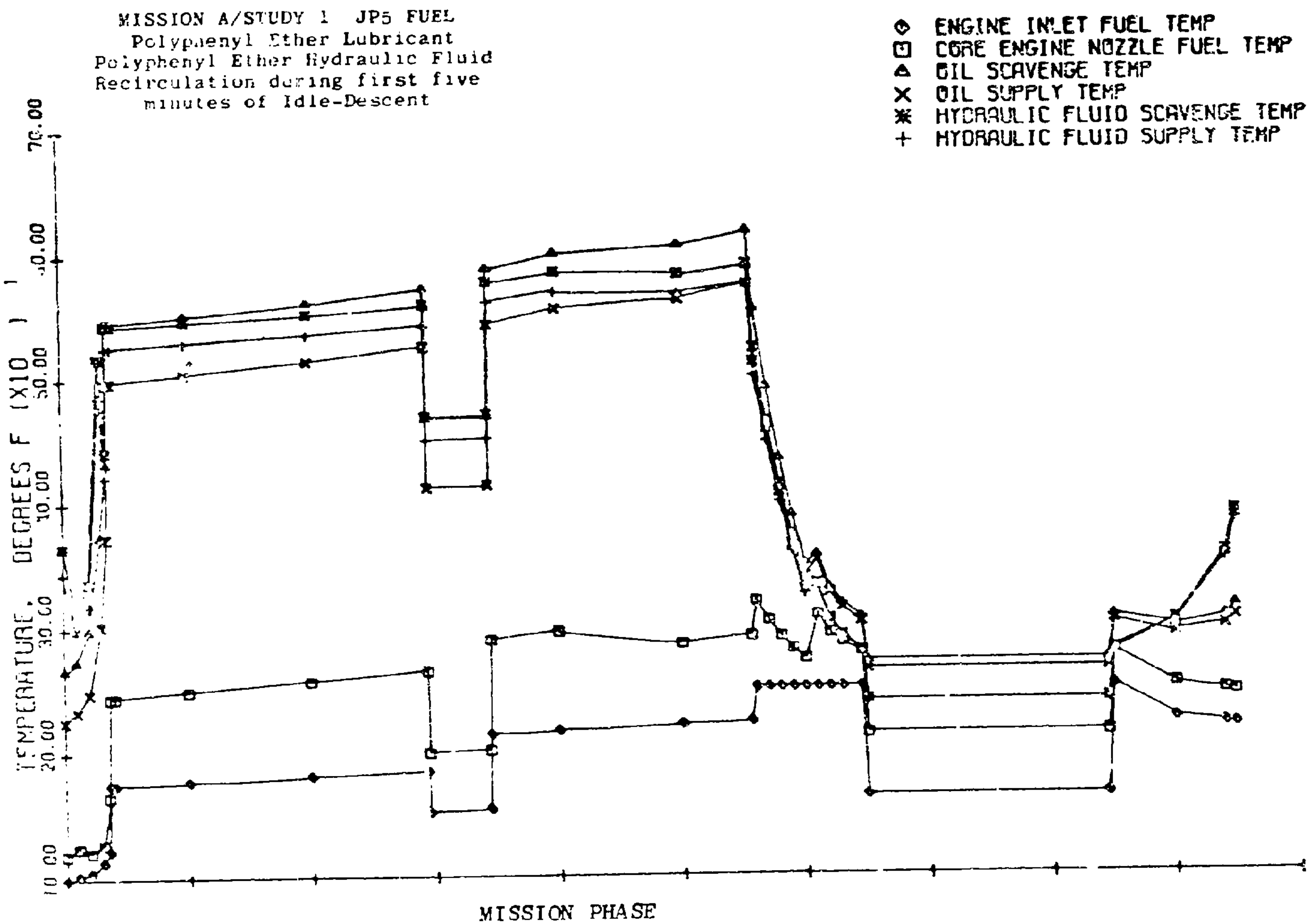



Figure 45. GE16/FLITE-1B Thermal Profiles, Polyphenyl Ether.

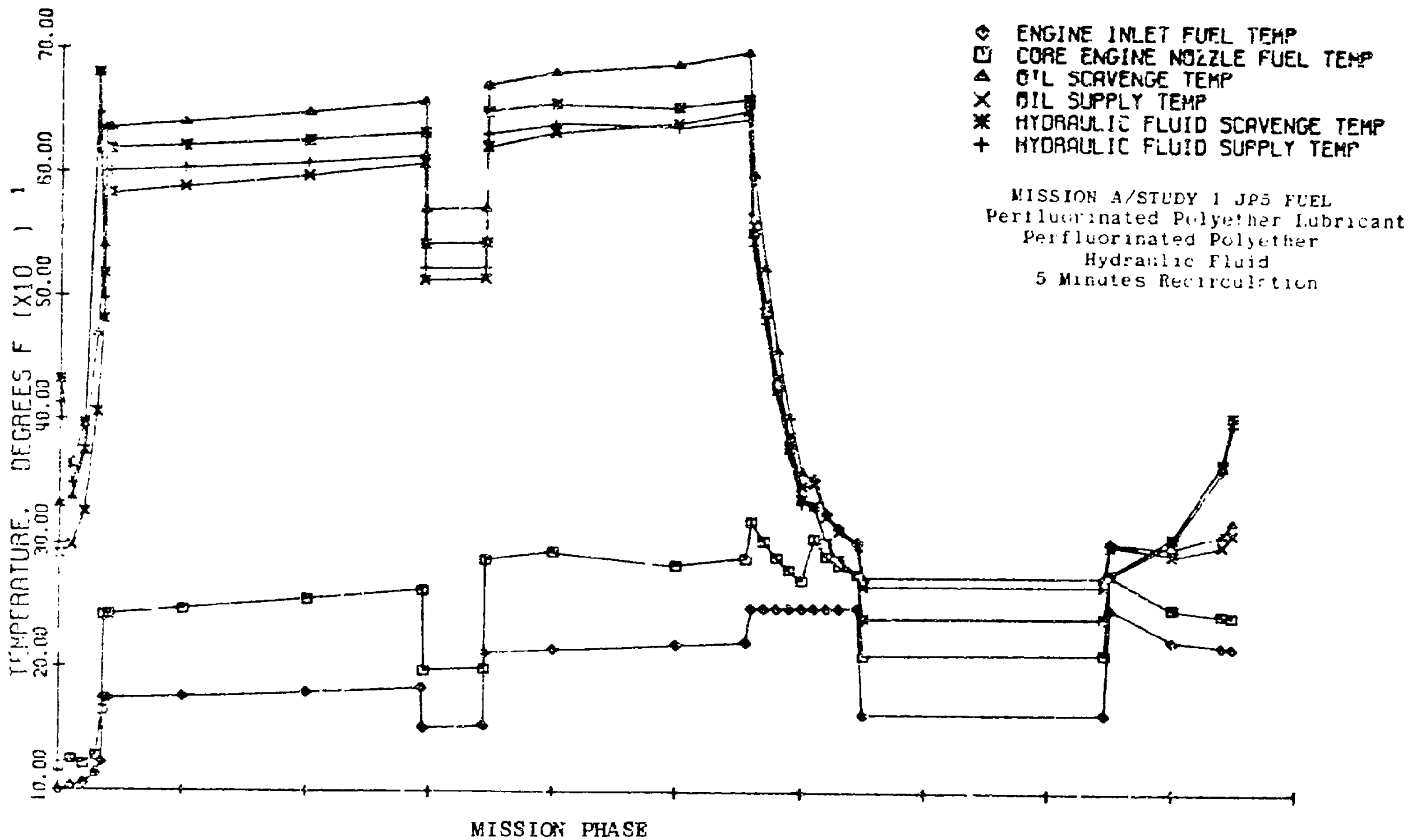



Figure 46. GE16/FLITE-1B Thermal Profiles, Perfluorinated Polyether.

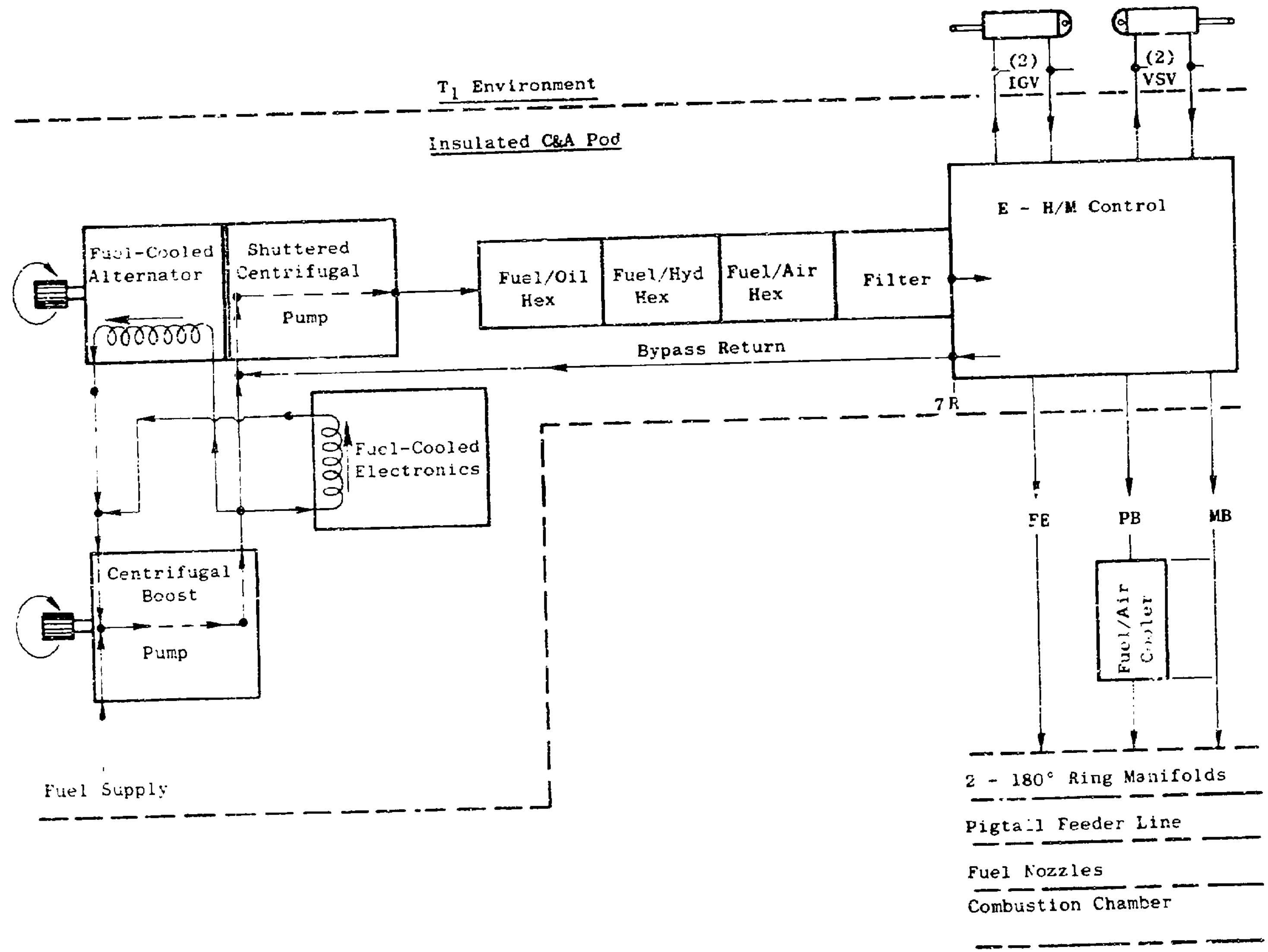



Figure 47. Mission A/Study 2 Fluid System Schematic.

A summary of the engine weight changes for the use of the four candidate lubricants in the GE16/FLITE-1C engine is shown in Table XXIV.

Table XXIV GE16/FLITE-1C Engine Weight Changes for the Candidate Lubricants. LP Turbine Fuel/Air Cooler, 129.50% Engine Size.

| System | MIL-L-27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|
| | Lubricant/Hydraulic Fluid | | | |
| Fuel | 80.9 lb | 80.9 lb | 80.9 lb | 80.9 lb |
| Fluid Power | 0 | 0 | 6.9 | 38.0 |
| Lubrication | 0 | -4.8 | -7.0 | 18.6 |
| Total | 80.9 lb | 76.1 lb | 80.1 lb | 137.5 lb |

Although the maximum fuel temperature has been increased to 700° F, recirculation during idle-descent is still needed to maintained the lubrication sytem and fluid power system temperatures within the operating temperature limits defined for each of the candidate lubricants. These recirculation flow rates and their associated fuel weight penalties, summarized in Table XXV, follow the trend of the bulk oil stability temperatures more significantly than the predecessor GE16/FLITE-1B system as the fuel no longer requires the elevated temperature protection.

Table XXV. Mission A Study 2 Recirculation Fuel Flow Rates, 129.50% Engine Size.

| Lubricant | Max. Flow Rate (pph) | Duration (min) | Weight Increment (lb) |
|---|---|---|---|
| MIL-L-27502 | 4,250 | 3 | 212 |
| 500° F Ester | 3,500 | 2 | 117 |
| Polyphenyl Ether | 2,800 | 2 | 93 |
| Perfluorinated Polyether | 2,000 | 1 | 33 |

Figures 48 through 51 depict results of flying the mission with JP-7 fuel and with each of the candidate lubricants. The fuel recirculation is maintained after the initiation of idle-descent, ranging from a maximum of 3 minutes for

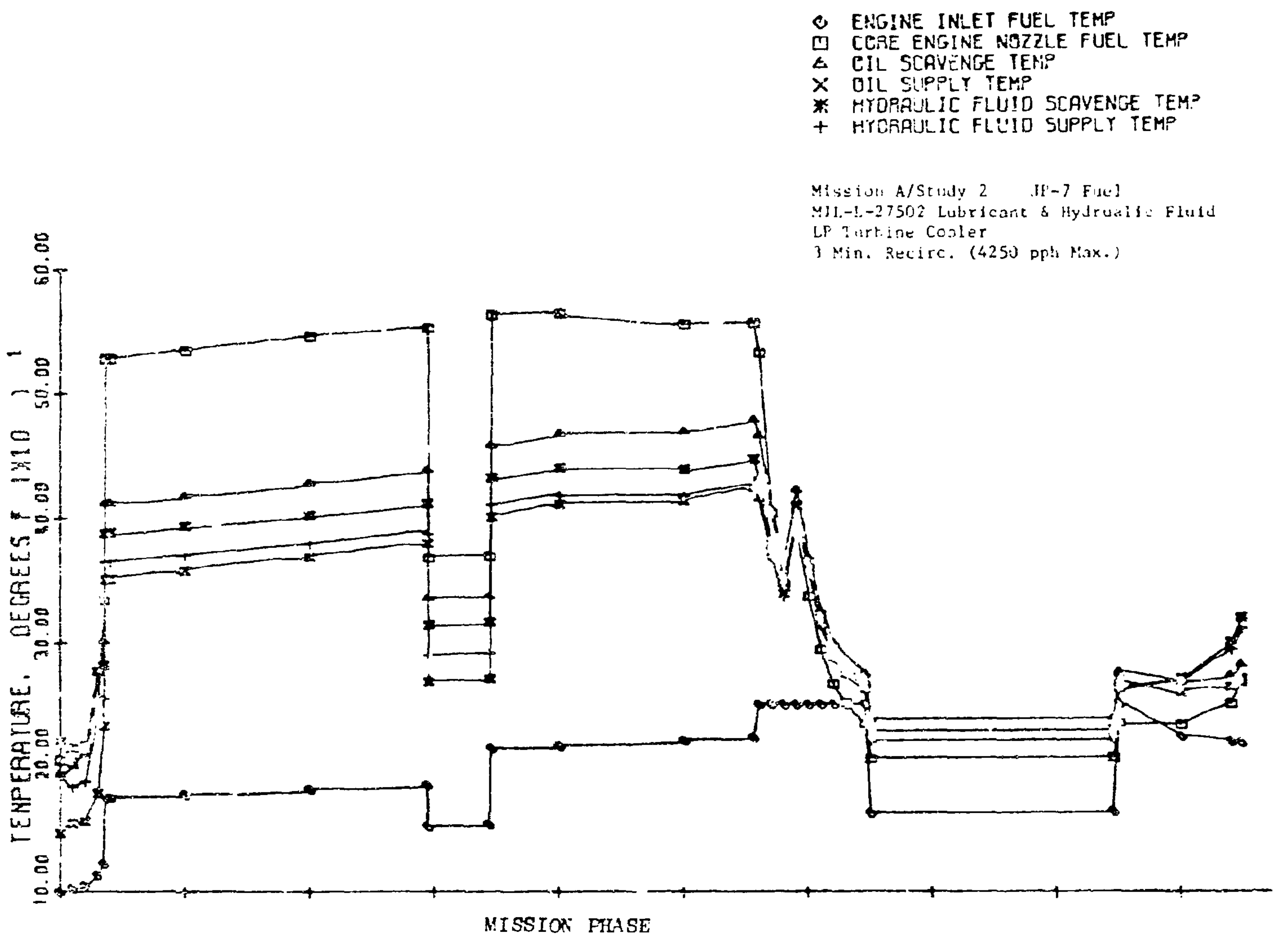



Figure 48. GE16/FLITE-1C Thermal Profiles, MIL-L-27502.

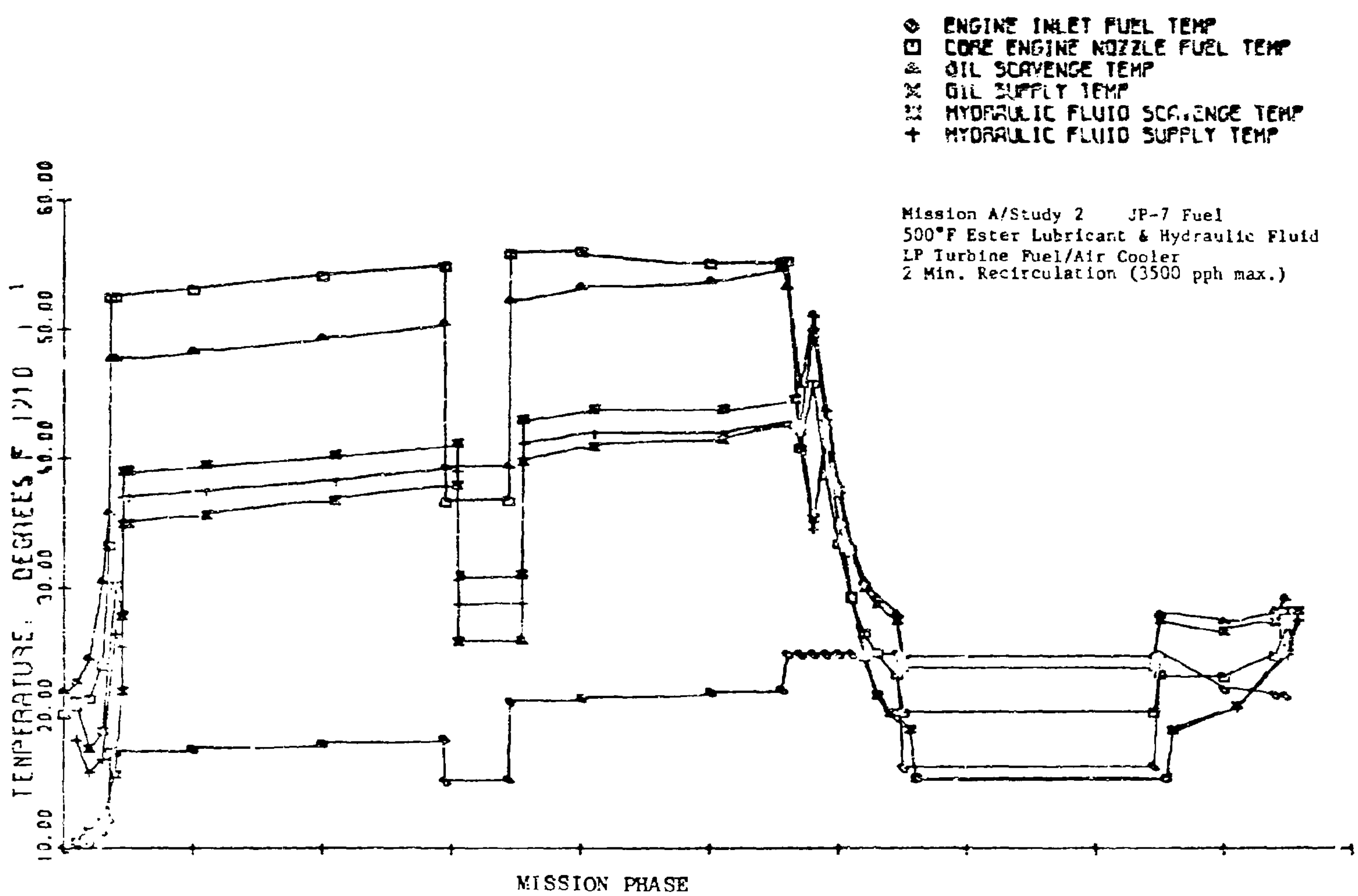



Figure 49. GE16/FLITE-1C Thermal Profiles, 500° F Ester.

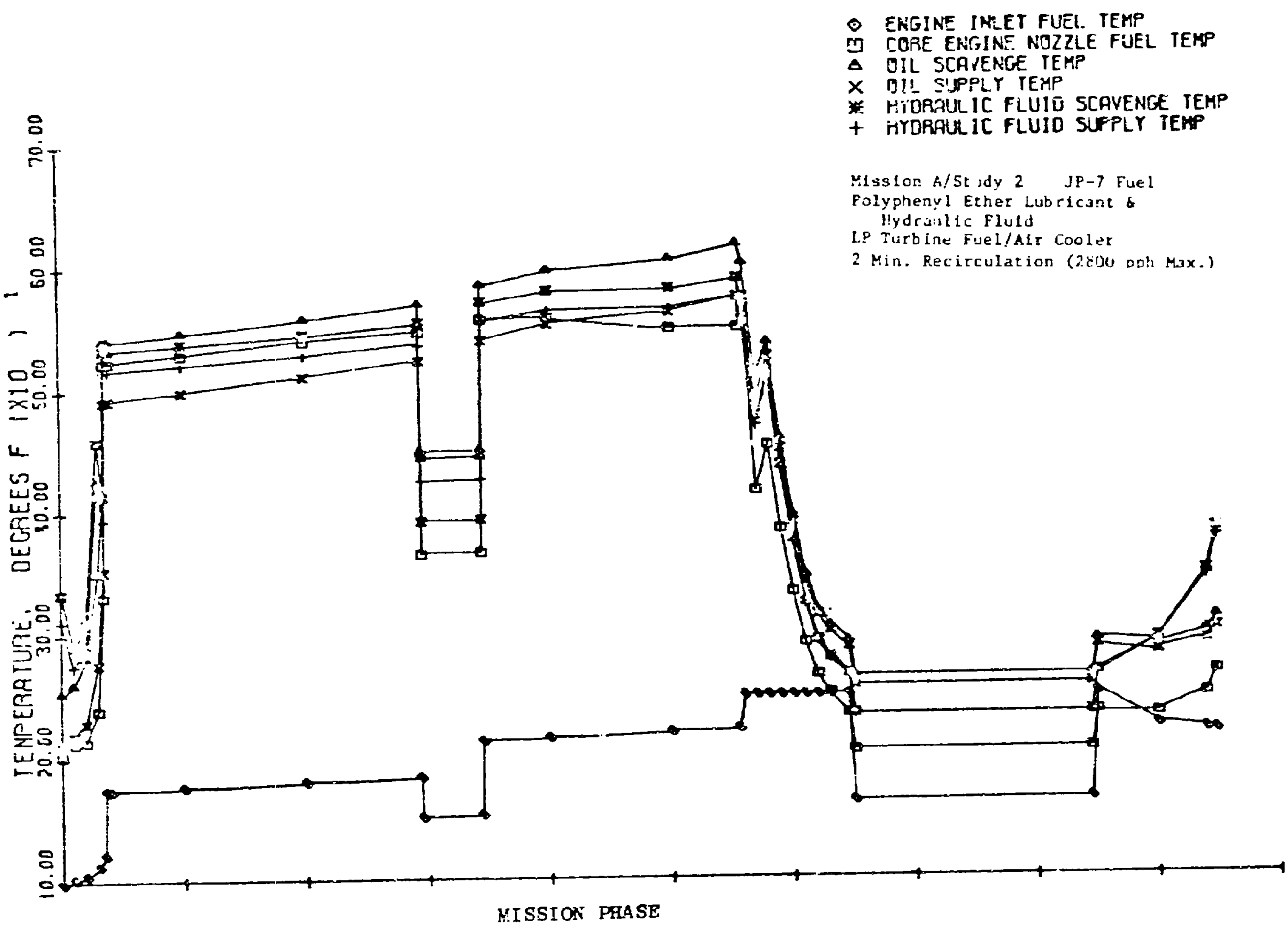



Figure 50. GE16/FLITE-1C Thermal Profiles, Polyphenyl Ether.

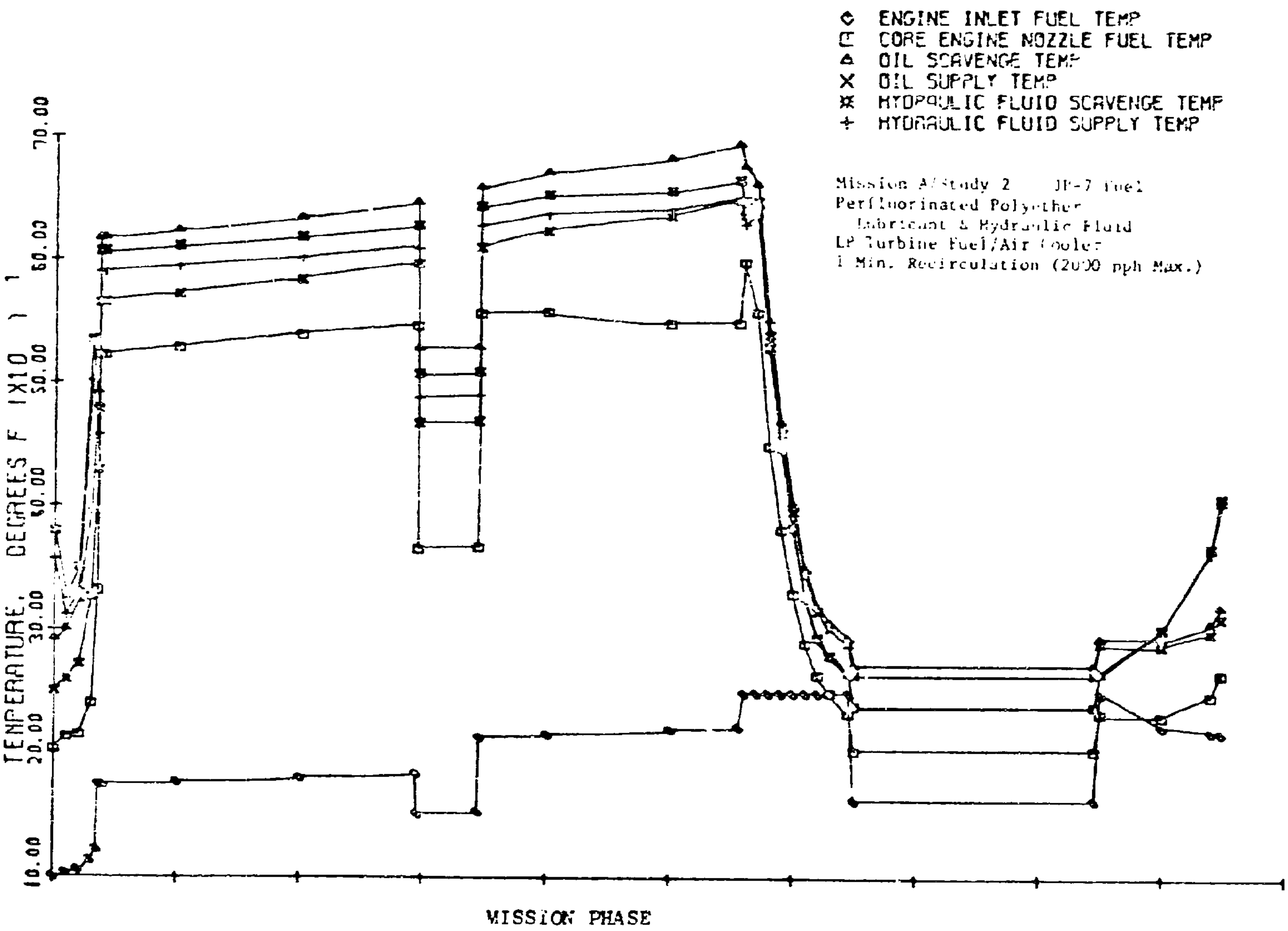



Figure 51. GE16/FLITE-1C Thermal Profiles, Perfluorinated Polyether.

the MIL-L-27502 lubricant to a minimum of 1 minute for the perfluorinated polyether. This recirculation again permits operation of the lubrication and fluid power systems during the critical heat sink utilization phase of the mission.

### B.3 Supplemental Study

As a perturbation of the Study 2 effort, it was decided to investigate the use of the JP-7 heat sink by the airframe. This was in line with the desire to determine the optimum method of heat sink utilization for the mission.

Figure 52 shows the GE16/FLITE-2D fluid system. This system uses JP-7 fuel at a maximum inlet fuel temperature of 350° F, having replaced the LP turbine cooling air fuel/air heat exchanger of Study 2 by a modified aircraft ECS. An engine gear driven refrigeration unit weighing approximately 8 pounds is necessary to cool the alternator and electronic control as a maximum of 280° F must be maintained in these components to provide adequate reliability.

A summary of the fuel delivery and fluid power system weight changes is presented in Table XXVI. The lubrication system weight remained unchanged from that defined for Study 1. A summary of the total engine weight changes for the use of the four candidate lubricant and hydraulic fluids in the GE16/FLITE-1D engine is shown in Table XXVII.

Figure 53 shows the interface fuel temperature profile for the modified aircraft ECS design that permits the replacement of the ram air heat exchanger while allowing the maximum interface fuel temperature to rise to a maximum of 350° F. The GE16 thermal model was executed using this profile and 500° F ester lubricant and produced the system temperature profiles as shown in Figure 54. Allowing the interface fuel temperature to rise produced approximately a twenty four pound weight penalty to the engine when compared to the baseline GE16/FLITE-1A design. This weight addition was due primarily to piping material changes from titanium to stainless steel and to provide thermal protection for the electronics. The recirculation fuel flow during idle descent was reduced from 3,500 pph to 2,700 pph maximum for the same 2 minute duration period.

Table XXVII. GE16/FLITE-1D Engine Weight Changes for the Candidate Lubricants, 129.50% Engine Size.

| System | Lubricant/Hydraulic Fluid: MIL-L-27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|
| Fuel | +17.6 lb | +17.6 lb | +17.6 lb | +17.6 lb |
| Fluid Power | 0 | 5.8 | 6.5 | 38.4 |
| Lubrication | 0 | -4.6 | -6.7 | 17.7 |
| | +17.6 lb | +18.6 lb | +17.4 lb | +73.7 lb |

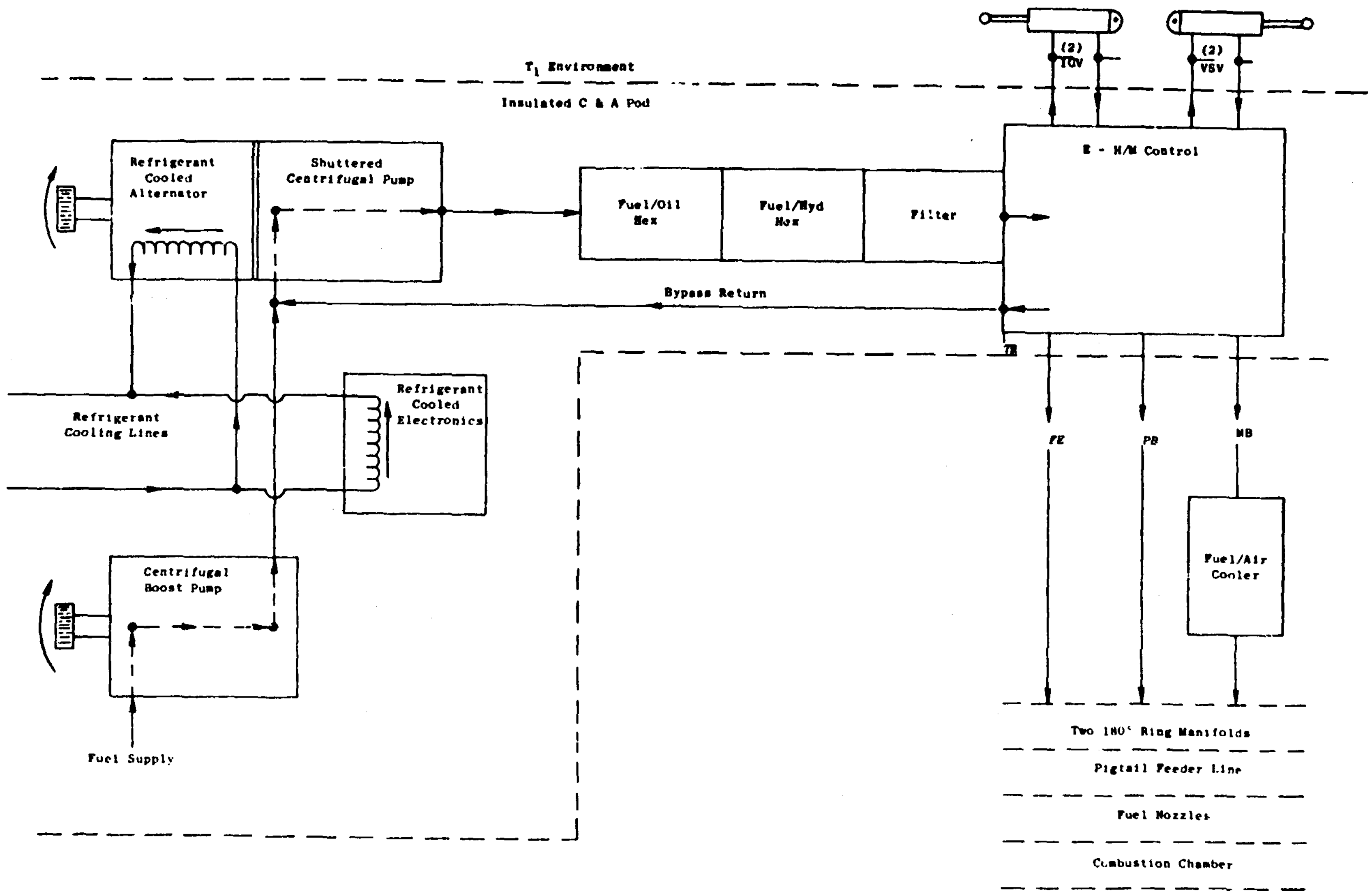



Figure 52. GE16/FLITE-1D Fluid System Schematic.

Table XXVI. Fuel Delivery System and Fluid Power System Weight Comparison, GE16/FLITE-1D Engine vs. GE16/FLITE-1A Baseline Engine.

| Fuel and FPS Components (1) | Fuel System (ΔWt-lb) FLITE-1A JP5 at 200° F | FLITE-1D JP7 at 350° F | Fluid Power System (ΔWt-lb) Base MIL-L-27502 | GE16/FLITE-1D MIL-L-27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|---|---|---|
| Main Engine Control | 35 | 42 | | | | | |
| Recirculating Fuel System | None | 2.9 | | | | | |
| Refrigerator | 0 | 8.3 | | | | | |
| Insulation (Min-K) | 8.4 | 7.8 | 4.0 | 4.0 | 4.0 | 3.1 | 2.6 |
| **FPS** | | | | | | | |
| Fluid 203 $in^3$ at 80° F | | | 7.19 | 7.19 | 7.19 | 8.81 | 13.98 |
| Integral Hyd Pump (Hidum-inum ≤450° F | | | 19.2 | 19.2 | 25.0 | 25.0 | 28.2 |
| Other Hyd. Components (T ≤ 550° F) | | | 8.4 | 8.4 | 8.4 | 8.4 | 10.7 |
| Titanium Piping & Brackets 550° F | | | 5.2 | 5.2 | 5.2 | 5.2 | 8.2 |
| 4-$A_{18}$ Actuators | | | 17.1 | 17.1 | 17.1 | 17.1 | 28.9 |
| $A_9$ Rot. Motor | | | 17.2 | 17.2 | 17.2 | 17.2 | 24.1 |
| ΔWt Penalty | Base | +17.6 | Base | Same | 5.8 | +6.52 | +38.4 |

(1) Only components having weight changes are listed.

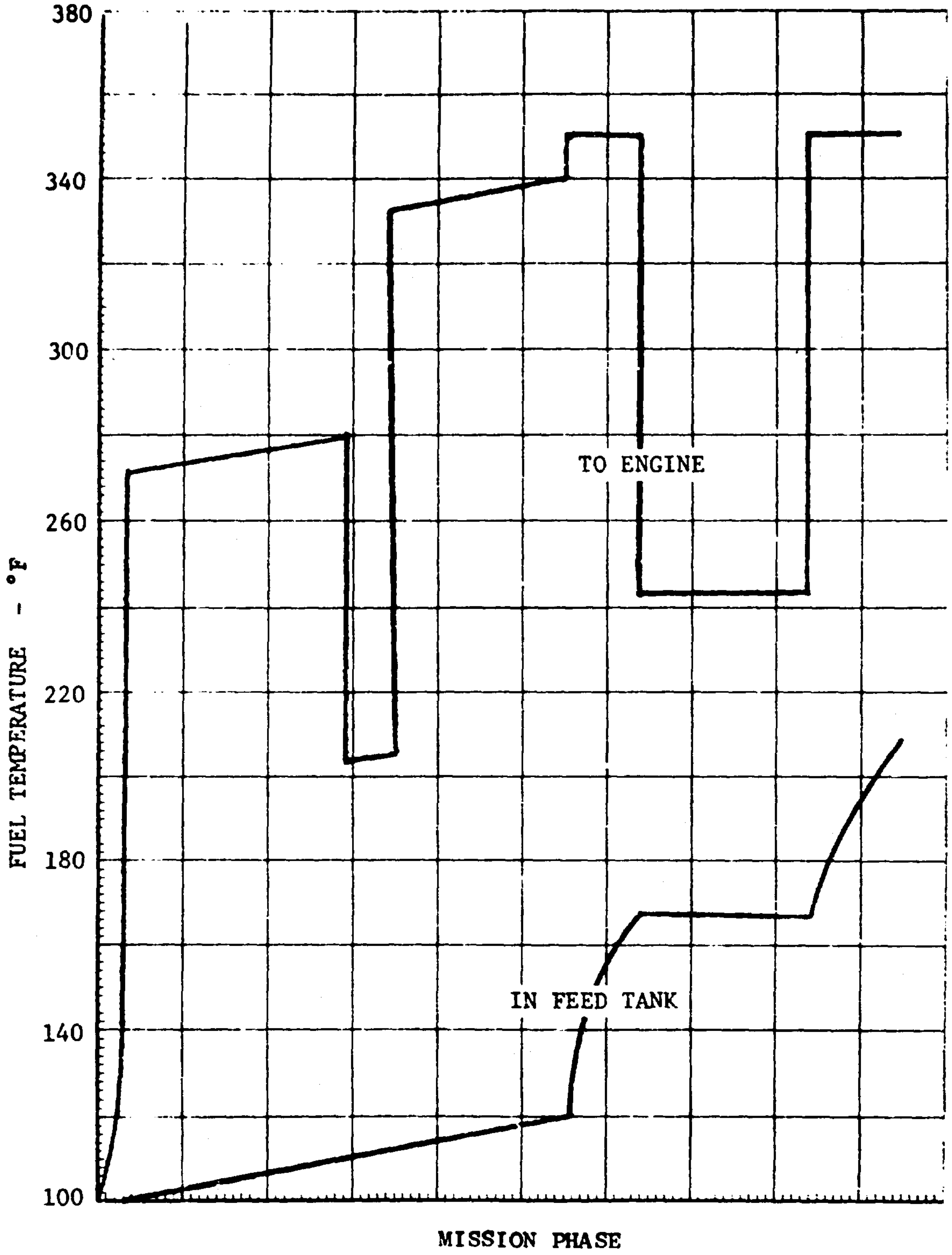



Figure 53. Mission A Fuel Temperatures, 350° F Interface.

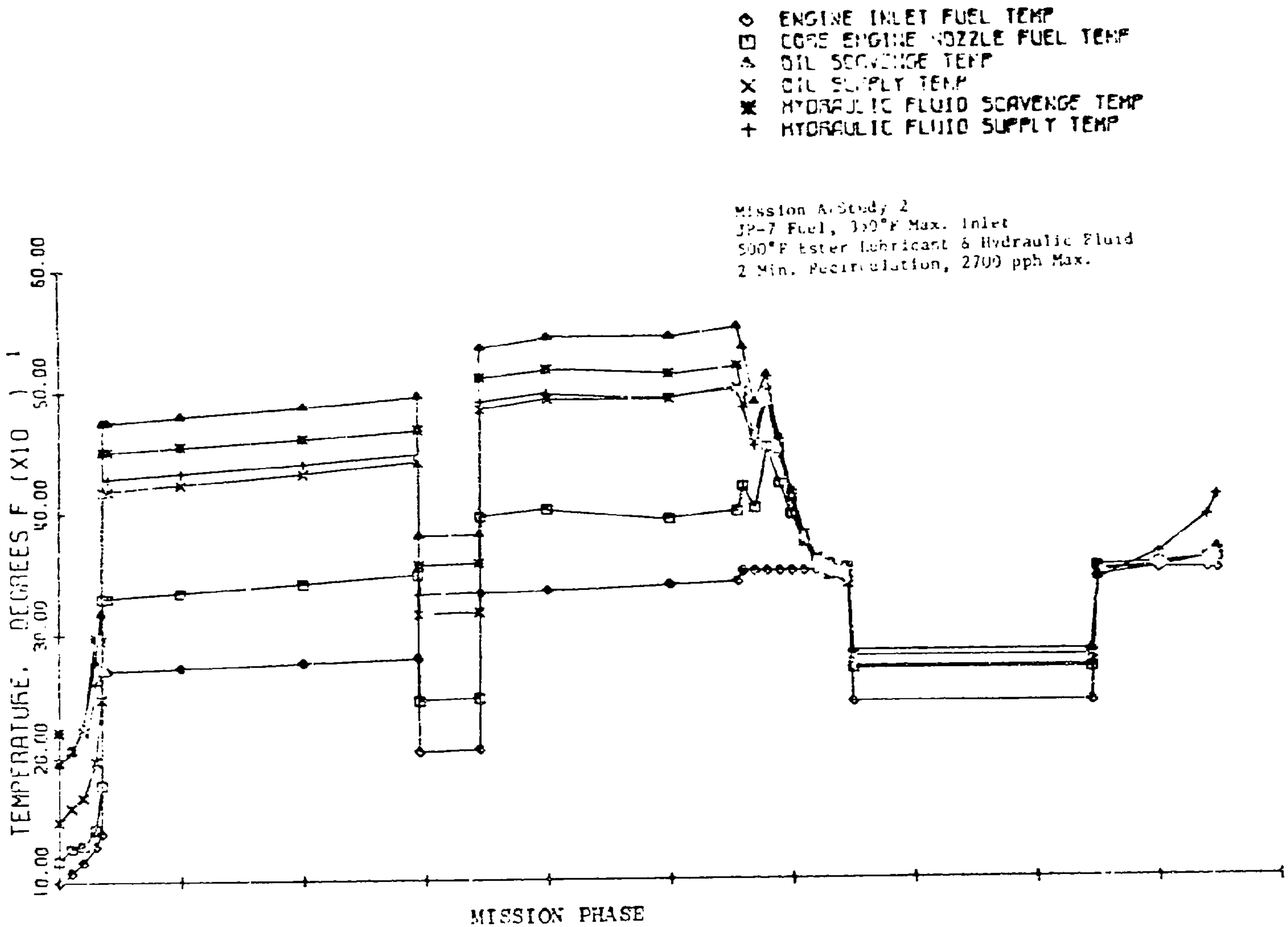



Figure 54. GE16/FLITE-1D Thermal Profiles, 500° F Ester, 350° F Interfaced Fuel Temperature.

C. Interceptor Design and Performance

The program objective for the mission interceptor evaluation was the comparison and ranking of the effects of fuel and lubricants selection on engine performance and resulting interceptor performance. A JP-5 fueled GE16/FLITE-1B engine and a JP-7 fueled GE16/FLITE-1C engine were evaluated in Study 1 and Study 2, as shown in Table XXVIII, for the matrix of four engine lubricants at an engine/airframe interface temperature of 250° F Because both fuels investigated were limited to the same interface temperature, the airframe subsystem performance and weights are identical for both interceptors. The resulting interceptors therefore provide a direct measure of the impact of engine performance on aircraft size.

Table XXVIII. Mission A Summary.

| | Study 1 | Study 2 |
|---|---|---|
| Engine–GE16/FLITE- | 1B | 1C |
| Fuel | JP-5/8 | JP-7 |
| Lubricant | Polyphenyl ether | 500° F ester |
| Engine Weight (lb) 100% uninstalled | 3,195 | 3,276 |
| Engine/Airframe Interface Fuel Temp. (° F) | 250 | 250 |
| Fuel Loading Temp. | Ambient | Ambient |
| Fuel Density ($lb/ft^3$) @ Loading Temp. | 51.8 | 51.8 |
| ECS Type | Air Cycle | Air Cycle |
| ECS Weight (lb) | 1,025 | 1,025 |

The increased fuel heat sink available with the JP-7 class fuel (Study 2) provides improved engine thrust and SFC relative to the use of JP-5/8 fuel (Study 1). The net result of the engine performance changes is an approximate 1000 lb reduction in aircraft TOGW.

The influence of lubricant selection on engine weight and resulting interceptor performance is of second order as compared to fuel effects with the exception of perfluorinated polyether. The minor weight variation discussed in subsequent sections cannot be considered of enough significance to permit specific lubricant selection recommendations.

### C.1 Interceptor Design

The converged mission interceptors are illustrated in Figure 55. These configurations were sized for the FLITE mission. Major system characteristics are presented in Table XXIX.

Table XXIX. Mission A Performance Characteristics

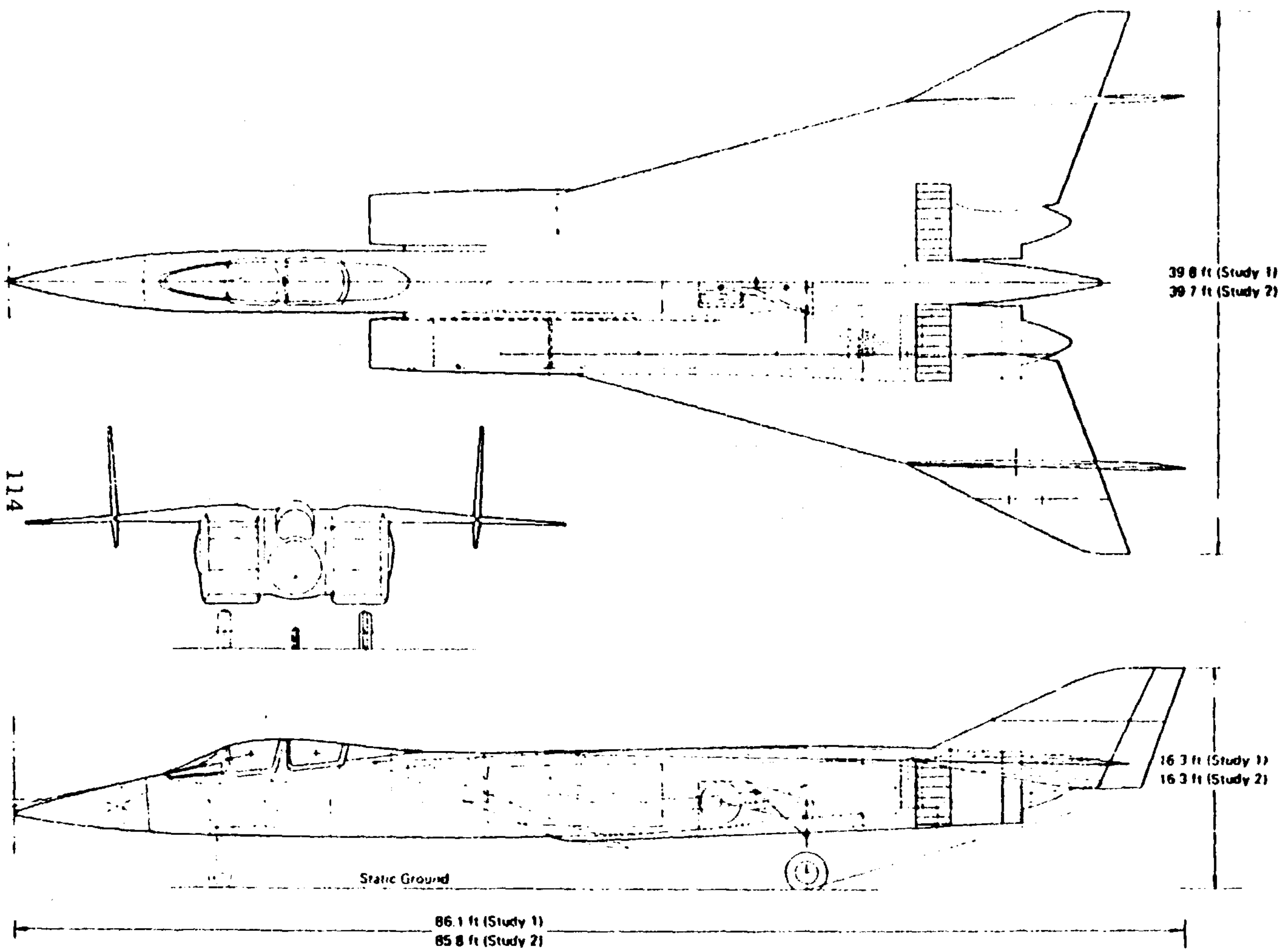
| | Study 1 | Study 2 |
|---|---|---|
| Wing Area, Including Tips | 1,074 $ft^2$ | 1,066 $ft^2$ |
| Take-off Gross Weight | ≈70,000 lb | ≈69,000 lb |
| Fuel Fraction | 0.50 | 0.50 |
| 2 GE16/FLITE Engines Thrust each, SLS uninstalled | -1B (33,975 lb) | -1C (33,850 lb) |
| Fuel | JP-5/8 | JP-7 |
| Engine/Airframe Interface Fuel Temperature | 250° F | 250° F |
| Engine Lubricant | Polyphenyl Ether | 500° F Ester |

A decrease of ≈ 1,000 lb in the take-off gross weight for the Study 2 aircraft reflects the improvements in engine performance obtained through the use of the higher heat sink capability available with a JP-7 class thermal stability fuel. The crew, avionics, payload, and inlet sizing criteria are identical for all the Mission A interceptors.

### C.2 Mission Performance

The GE16/FLITE-1A propulsion system described in Section III was modified to reflect changes in fuels and lubricants for Study 1 and Study 2.

The change from MIL-L-27502 lubricant for the reference size baseline engine to polyphenyl ether for the Study 1 GE16/FLITE-1B engine results in no




| Propulsion | |
|---|---|
| (2) GE16/FLITF Turbofan Engines | |
| Inlet | 2-D Overhead Ramp |

| Armament and Fire Control |
|---|
| 4 Long Range Air-to-Air Missiles at 640 lb Each |
| 36 in. Dish Radar (Modified AWG 9) |

| Physical Characteristics | Wing | Wing Tip | Vert Tail |
|---|---|---|---|
| Aspect Ratio | 1.06 | 1.56 | 0.706 |
| Taper Ratio | 0.236 | 0.211 | 0.330 |
| Dihedral | $-3^{\circ}$ | $-3^{\circ}$ | - |
| Airfoil Section | NACA64A003 | NACA64A003 | NACA64A003 |
| Airfoil Thickness | 3% | 3% | 3% |
| Leading Edge Sweep | $75^{\circ}$ | $63.5^{\circ}$ | $65^{\circ}$ |
| Trailing Edge Sweep | $20^{\circ}$ | $20^{\circ}$ | $20^{\circ}$ |

Figure 55. Mission A Interceptor

change in performance chacteristics and only a slight change in engine weight due to changes in the lubricant and fluid power system, Table XXX. Using JP-7 fuel and 500° F ester lubricant in the GE16/FLITE-1C, however, provides an increase in thrust and engine weight and a slight reduction in specific fuel consumption when compared to the GE16/FLITE-1B as shown in Table XXX. These changes in engine performance are achieved through utilization of the increased JP-7 heat sink to reduce the low pressure turbine cooling air requirement.

The air induction systems are identical to the baseline vehicle discussed in Section III. The airflow for each alternate engine remained unchanged from the reference size baseline engine, permitting the inlet to remain unchanged in size and performance.

Installed engine performance is presented in Table XXXI and SFC ratios relative to the GE16/FLITE-1B engine at selected mission segments. Although the uninstalled weight for the -1C is greater than the -1B weight, the improved SFC's and engine thrust for the GE16/FLITE-1C engine reduced the interceptor TOGW by ~1,000 lb and reduced the installed engine weight by 35 lb.

Table XXX. GE16/FLITE Engine Characteristics.

| | | GE16/FLITE-1B | GE16/FLITE-1C |
|---|---|---|---|
| $F_{N_{max}}$ (SLS) | (lb) | 26,160 | 26,800 |
| $SFC_{max}$ (SLS) | (lb/hr/lb) | 1.96 | 1.95 |
| Airflow (SLS) | (lb/sec) | 2.77 | 2.77 |
| Weight* | (lb) | 3,195 | 3,276 |
| Fuel | | JP-5/8 | JP-7 |
| Fuel Interface Temperature | (°F) | 250 | 250 |
| Lubricant | | Polyphenyl Ether | 500° F Ester |

* Includes nozzle, engine/nozzle controls and accessories.
Excludes airframe mounted accessories, accessory gear box and starter.

Table XXXI. GE16/FLITE Installed Performance Characteristics.

| | GE16/FLITE-1B | | GE16/FLITE-1C | |
|---|---|---|---|---|
| Mission Segment | $F_N/F_{N_{Ref}}$ | $SFC/SFC_{Ref}$ | $F_N/F_{N_{Ref}}$ | $SFC/SFC_{Ref}$ |
| SLS | 1.0 | 1.0 | 1.025 | 0.997 |
| Acceleration | 1.0 | 1.0 | 1.015 | 0.995 |
| Combat | 1.0 | 1.0 | 1.016 | 0.996 |
| Cruise | 1.0 | 1.0 | 1.027 | 0.999 |

C.3 Alternate Lubricants

The influence of lubricant selection on engine weight for both the GE16/FLITE-1B and GE16/FLITE-1C engines is presented in Table XXXII. These weights were used to select polyphenyl ether and 500° F ester as the best lubricants for the GE16/FLITE-1B and GE16/FLITE-1C engines respectively. The minor variations in engine weight between MIL-L-27502, 500° F ester, and polyphenyl ether results from small changes in both the engine fluid power and lube system weights to accommodate the variation in lubricant bulk temperature capability and physical properties. Due to perfluorinated polyether's low bulk modulus, a sizable increase in fluid power system component weights was incurred. The high vapor pressure of perfluorinated polyether and attendent high oil consumption in a vented lube system also required the use of a non-vented system which caused an additional weight increase.

Table XXXII. Engine Weight Sensitivity.

100% Engine Size

SLS Air Flow = 277 pps

| | MIL-L-27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|
| GE16/FLITE-1B | 3,200 | 3,195 | 3,194 | 3,232 |
| GE16/FLITE-1C | 3,281 | 3,276 | 3,281 | 3,337 |

These "best" engine/lubricant combinations were then performed and the impact of alternate lubricants on TOGW determined as sensitivities to the performed aircraft. The variations in aircraft TOGW to account for the changes in engine weight arising from the use of alternate lubricants are presented in Table XXXIII. Although polyphenyl ether and 500° F ester provide the lightest Study 1 and Study 2 interceptors, respectively, use of the alternate lubricants with the exception of perfluorinated polyether imposes only minor weight penalties (less than 50 lb).

Table XXXIII. Impact of Lubricant Selection on Interceptor Size.

| | MIL-L-27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|
| ΔTOGW Study 1 (lb) (GE16/FLITE-1B Engine) | 0 | -50 | -50 | +320 |
| ΔTOGW Study 1 (lb) GE16/FLITE-1C Engine) | 0 | -50 | 0 | +450 |

$\Delta TOGW = TOGW_{MIL-L-27502} - TOGW$

## C.4 Thermodynamic Characteristics

Both Studies 1 and 2 were based on maximum interface temperature of 250° F with the differences in available fuel heat sink reflected in engine performance. An analysis using the airframe heat loads summarized in Table II and engine fuel flow rates typical of each mission phase, results in the fuel temperature profiles presented in Figure 53. Based on an initial fuel temperature of 100° F, engine fuel demands are sufficient to maintain the engine/airframe fuel interface below 250° F except during the descent phase of the mission. During the initial stages of descent, sufficient fuel is pumped from the feed tank to absorb the airframe heat loads without exceeding 250° F with the excess fuel recirculated to the feed tank. The combined effects of heat transfer to the fuel due to recirculation and aerodynamic heating results in a bulk fuel temperature rise of only 35° F.

## C.5 Supplemental Studies

The primary intent of the mission evaluation was to determine the performance differences resulting from the use of JP-5 (Study 1) and JP-7 (Study 2) with the matrix of four engine lubricants. This evaluation was performed with an engine airframe fuel interface temperature of 250° F for both the JP-5 and JP-7 fueled configurations. As the interface temperature is the same for both fuels, the increased heat sink capacity of JP-7 was used to improve engine performance without regard to airframe system design. Use of JP-7's higher heat sink to improve engine performance provided an approximate 1,000 lb reduction to TOGW relative to Study 1.

A supplemental study was performed to determine if a higher allowable interface temperature would enable simplification and/or weight reduction of airframe systems. To take advantage of the increased fuel heat sink capacity of JP-7, the Mission A interceptor ECS was modified to use only fuel as a heat sink thereby eliminating the need for ram air. Figure 52 shows that by proper fuel management (recirculation) fuel can be delivered to the engines at or below 350° F without an excessive increase in stored fuel temperatures. Further increases in interface temperature to a value higher than 350° F offered no significant advantage.

An ECS weight reduction of 240 lb was achieved by (1) replacement of air-to-air heat exchangers with liquid-to-air heat exchangers; and (2) elimination of the ram air ducting system. A slight increase of 15 lb in fuel system weight was incurred due to an increase in fuel line length to accommodate addition of the primary fuel-to-air heat exchanger. Because of the higher engine fuel temperatures attendent with a 350° F fuel interface temperature, modifications to the GE16/FLITE-1A engine resulted in a 22 lb weight increase for each 100% engine. Elimination of the requirement for ECS ram air cooling resulted in a decrease of 1% reduction in inlet capture area and deletion of the ECS drag increment from the total air induction system drag.

The net result of these changes is a decrease of 1,200 lb in TOGW relative to the Study 1 interceptor. Since this weight reduction exceeds that achieved by using the higher heat sink of JP-7 to improve engine performance, this concept provides a more attractive interceptor.

An additional evaluation was performed to assess the potential benefits of using precooled fuel (0° F), liquid-cooled avionics, recirculation of cockpit air, and a direct sink ECS. Using interceptor sensitivities to account for changes in ECS weight engine bleed air, and increased fuel density, a reduction of 9,500 lb would be expected. A breakdown of these effects relative to Study 2 is presented in Table XXXIV.

Table XXXIV. Mission A Precooled Fuel Weight Summary.

| | ΔTOGW (lb) |
|---|---|
| ΔECS Wt = -635 lb | -2,540 |
| ΔFuel Density = +1.2 $lb/ft^3$ | -500 |
| ΔTOGW due to elimination of Ram Air | -325 |
| ΔEngine Bleed Air = 97 ppm | -1,135 |
| Total ΔTOGW | -4,500 |

This analysis is based on first order effects and represents an approximate weight reduction which can be obtained by using precooled fuel.

# SECTION V

## MISSION B RESULTS

### A. Utilization of Fuel Heat Sink

#### Heat Exchanger Designs

Studies were made to determine the potential use of excess fuel heat sink for cooling combustor and exhaust system components in the GE14/FL TE-2A engine. This excess fuel heat sink was considered to be the difference between the maximum permissible fuel temperature, as listed in Table XXXV, and the fuel temperature at the exit of the main engine control.

Table XXXV. Mission B Maximum Fuel Temperatures.

| Mission | Fuel | $T_{fuel\ max}$ ° F | Comments |
|---|---|---|---|
| B | JP-4/5/8 | 475 | Several Missions/Cleanable |
| | JP-7 | 700 | Several Missions/Cleanable |
| | JP-7 | 1000 | Research Level |

From a screening of engine operating points along the flight path, it was established that the limiting Mission B fuel heat sink occurs at supersonic cruise where the fuel flow rates are reduced and where the fuel delivery temperature is highest. The fuel temperature rise usable as a heat sink for cooling combustor and exhaust system components is shown in Table XXXVI.

Table XXXVI. Mission B Available Fuel Heat Sink.

| Study | Fuel | $T_{Fuel\ Interface}$ (° F) | $T_{H-X\ in}$ (° F) | $T_{Allow.}$ (° F)(1) | $\Delta T_{Avail.}$ (° F) |
|---|---|---|---|---|---|
| Base | JP-5 | 200 | 250 | 375 | 1.5 |
| 1 | JP-4/5/8 | 150 | 200 | 375 | 175 |
| 2 | JP-5/8 | 250 | 300 | 375 | 175 |
| 3 | JP-5/8 | 350 | 400 | 375 | 175 |
| 4 | JP-7 | 250 | 300 | 600/1000 | 300/700 |
| 5 | JP-7 | 350 | 400 | 600/1000 | 200/600 |

(1) - The listed allowable fuel temperatures are based on a fuel/wall temperature criteria and the assumption that an approximate 00-150° F ΔT exists between the fuel and its wall temperature.

Two candidate concepts were investigated for the utilization of the fuel heat sink in the Mission B studies. These were the following:

1. Direct fuel cooling of the exhaust nozzle plug.
2. Ram burner liner cooling air cooling.

The above two concepts represent typical application of fuel heat sink utilization in engine applications and were selected to realize benefits from engine design and/or cycle efficiency considerations. Specifically, direct fuel cooling of the nozzle plug was selected as the solution to solve the complex design problem in the baseline engine of how to practically utilize excess fuel heat sink. Cooling of the nozzle plug in the baseline engine is accomplished by the use of compressor discharge air. At operating points on the flight map where the core engine is shutdown, cooling of the aft region of the air-cooled plug requires the use of ram air. The use of both compressor air and ram air for plug cooling therefore requires the use of a dual cooling system. This presents considerable difficulties, both from mechanical and thermal design considerations. The consideration of the use of fuel to cool the plug not only contributes to some improvement in cycle efficiency, but also offers a reasonable solution to an otherwise difficult design problem.

Fuel cooling of the ram liner cooling air was selected upon evaluation of the maximum cycle benefits that can potentially be realized from this application.

The results of these investigations established the feasibility of direct fuel cooling of the aft region of the exhaust nozzle without exceeding presently established temperature limits for JP-7 applications. Cooling of the ram burner cooling air resulted in an average coolant temperature reduction of 425° F with a corresponding reduction of 50% in coolant flow rate at the engine sizing point.

These two cooling concepts were considered for use with each of the four studies of Mission B. Comparison with the GE14 thermal model results for Mission B/Study 1 (JP-4/5/8 @ 150° F) and for Mission B/Study 2 (JP-5/8 @ 250° F) indicate that both of these engine systems have only marginal heat sink capacity to justify the inclusion of either the exhaust nozzle or the ram burner liner cooling air heat exchanger concept. Furthermore, during ramjet idle-descent, the fuel temperatures at the combustor nozzles are in the range of 400° F to 450° F even with fuel recirculation. The additional heat load imposed by the ram burner or exhaust nozzle concepts would force the fuel recirculation fuel flow rates to rise to unacceptable levels. Therefore, the use of the two heat exchanger systems was considered feasible only for the Mission B studies utilizing JP-7 fuel. Mission B/Study 3, JP-7 fuel at 250° F maximum engine inlet fuel temperature, was considered as the design reference condition for the heat exchanger concepts. The extension of the results to Mission B/Study 4 (JP-7 @ 350° F) was a straight forward process.

System 1 - (Exhaust Nozzle Plug Heat Exchanger)

The fuel heat exchanger for the divergent portion of the core exhaust nozzle plug and the heat exchanger design is shown in Figure 56. This design incorporates the basic features of the X-370 Ramburner/Afterburner fuel heat exchanger that was successfully demonstrated in a one-half scale model test. (Reference 17).

The heat exchanger consists of a conical plug with a 0.022-inch nominal skin thickness wrapped with 0.375-inch diameter tubes having a 0.010-inch wall thickness. These tubes are helically wound around the plug and serve as the

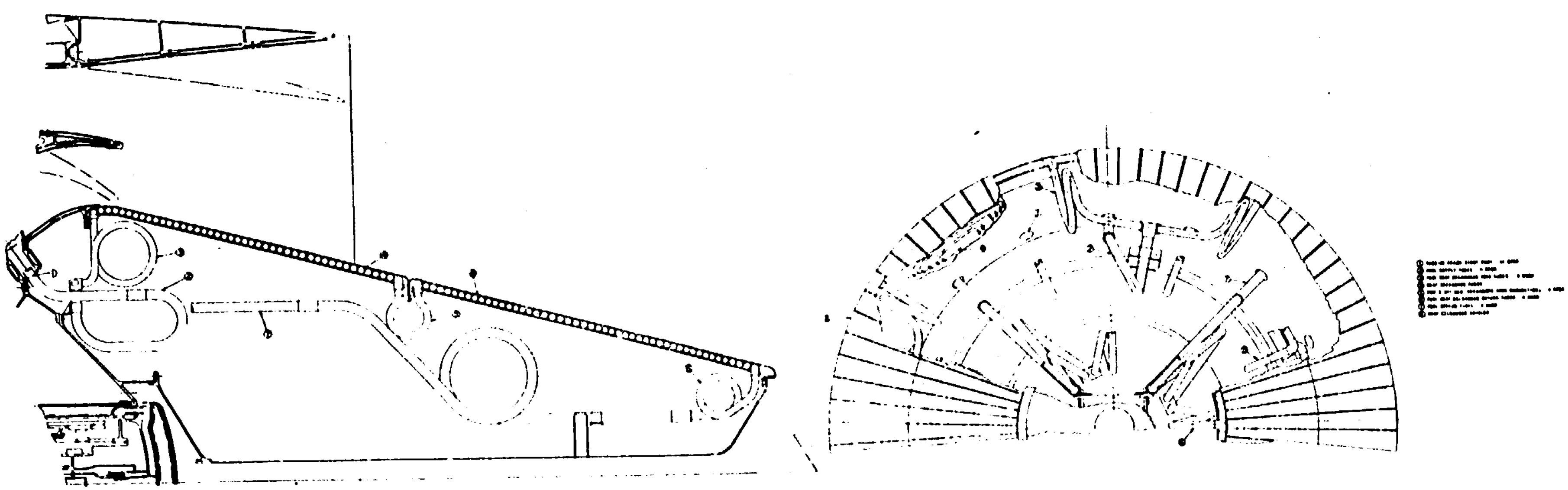


Figure 56. CE14/FLITE-2A Exhaust Nozzle Plug Heat Exchanger.

fuel heat exchanger and the means by which the plug structure is cooled. There are eight tubes in parallel that are connected through the plug at each end to four 0.50-inch supply tubes and four 0.50-inch return tubes. Four of the 16 turbine frame struts are used for the four fuel supply tubes and four other struts are used for the four fuel return tubes. Heat shields are applied to the hot-gas side of the heat exchanger to control the heat transferred to the fuel.

The heat exchanger tubes are brazed to each other and the heat shields are brazed to the tubes with the ends of each shield held between the plug flanges. The tubes are not brazed to the plug structural skin and a radial gap of 0.030-0.060 inch between the skin and tubes allows for differential growth between them. The plug is vented with compressor second stage air that pressurizes the plug to keep it in hoop tension.

The material selected for this design was René 41C to provide the lightest weight design. The associated weight increment to the baseline engine configuration is summarized in Table XXXVII.

Table XXXVII. Exhaust Nozzle Plug Heat Exchanger Weight Summary, 100% Engine Size.

| Component | | Weight |
|---|---|---|
| Fuel Supply Tubes | | 0.8 lb |
| Cooling tubes | | 21.7 |
| Jumper Tubes | | 0.2 |
| Fuel Return Tubes | | 1.3 |
| Fittings | | 0.7 |
| Clamps & Brackets | | 0.8 |
| Nuts & Bolts | | 0.4 |
| | Total | 25.9 lb |

Fuel side pressure drop and heat transfer coefficients are a function of the fuel flow rate gas unit flow area. Hence, fuel tube diameters and the number of fuel tubes required were determined by the allowable pressure drop and fuel tube surface temperature. The present design considers the use of JP-7 fuel and is based on a maximum allowable surface temperature of 700° F.

The exhaust nozzle plug heat exchanger design operating point was selected to correspond to the maximum heat load conditions encountered in the flight map. Some of the pertinent cycle data are tabulated in Table XXXVIII.

Table XXXVIII. Exhaust Nozzle Plug Heat Exchanger Design Point Cycle Operating Conditions.

100% Engine

| | |
|---|---|
| $T_8$ (° R) | 4,199 |
| $T_{28}$ (° R) | 4,170 |
| $P_8$ (psia) | 115.9 |
| $P_{28}$ (psia) | 89.8 |
| $W_F$ Duct (pph) | 41,000 |
| $W_{FC}$ (pph) | 40,500 |

The plug surface pressure distribution and calculated heat transfer coefficients and heat fluxes based on the above distribution are shown in Figure 57. The heat transfer coefficients were calculated using Eckert's reference enthalpy method (Reference 18) and are based on turbulent flat plate correlations. The heat fluxes shown include gas radiation which was estimated at about 10% of the total heat flux. The basic operating characteristics of the heat exchanger are shown in Table XXXIX.

The original design concept envisaged the use of the core engine fuel to cool the region of the plug up to the nozzle throat and the ram burner fuel aft of the nozzle throat. From heat sink availability considerations, this concept was established to be feasible, resulting in 130° F and 170° F temperature rise for the core engine and ram burner fuels, respectively, at the design point. This concept, however, resulted in difficulty in the cooling of the aft region of the plug at operating points where the ram burner is shutdown.

Table XXXIX. Fuel Cooled Nozzle Plug Heat Exchanger Operating Characteristics

100% Engine

| | |
|---|---|
| Tube Diameter (in) | 0.375 |
| No. of Tubes | 8 |
| Tube Length (ft) | 7.0 |
| Max. Surface Temperatures | |
| Brase Filled External Tube Design (° F) | 652 |
| Braze Internal Tube Design | 610 |
| Max. Heat Flux (Btu/hr ft$^2$ °F) | $7.1 \times 10^5$ |
| Gas Side Heat Transfer Coefficient (Btu/hr ft$^2$ °F) | 230 |
| Fuel Side Heat Transfer Coefficient (Btu/hr ft$^2$ °F) | 2,200 |
| Total Heat Load (Btu/hr) | $4.80 \times 10^5$ |
| Fuel Flow Rate (pph) | $4.05 \times 10^4$ |
| Fuel Exit Temperature (° F) | 470 |
| Pressure Drop (psia) | 32.5 |
| Fuel Residence Time (sec) | 0.15 |

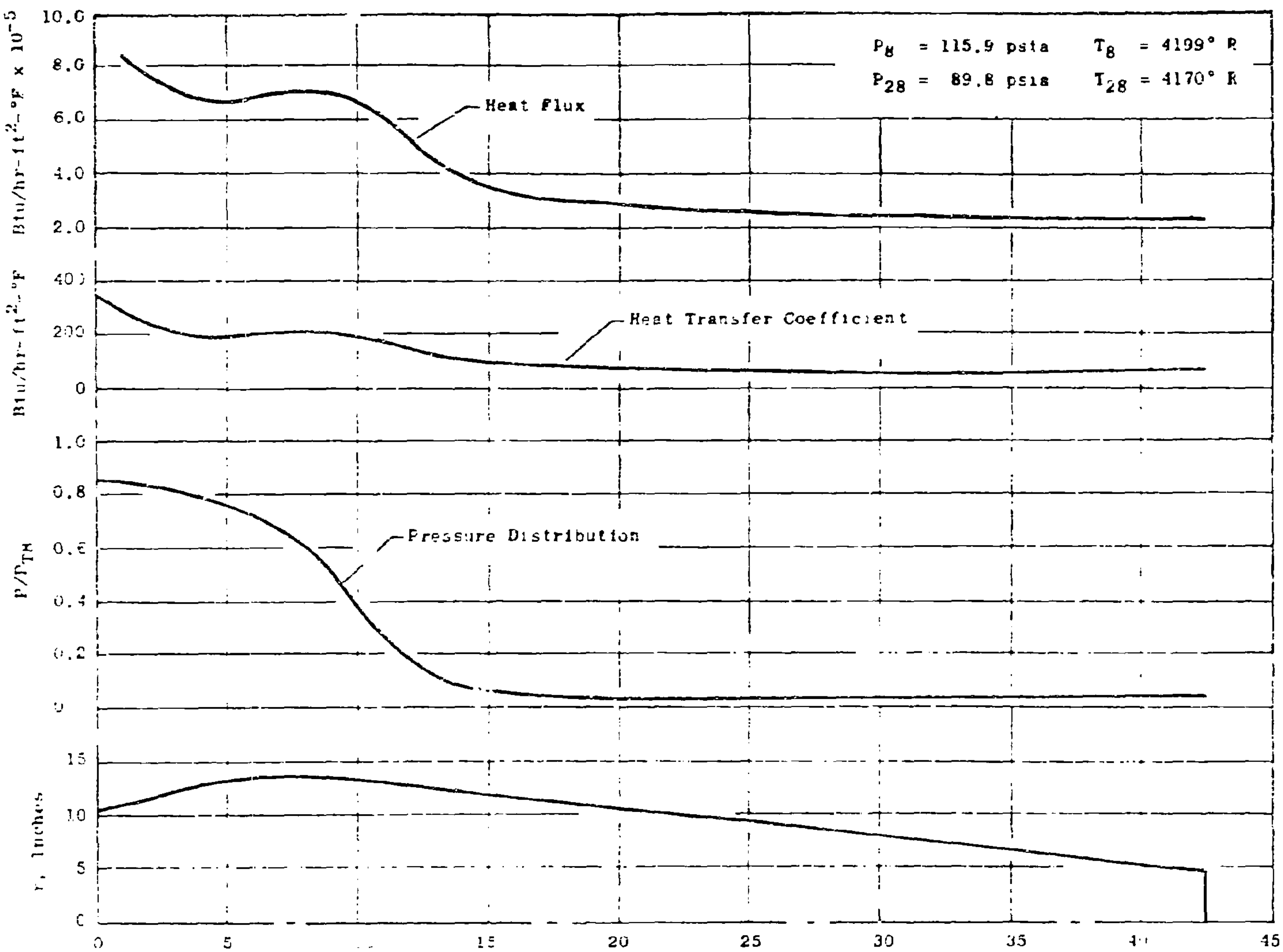



Figure 57. Exhaust Nozzle Plug Heat Exchanger Pressure Heat Transfer Coefficient and Heat Flux Distributions.

As a result, the final design concept that evolved considered air cooling of the forward region, and fuel cooling of the aft region of the plug. Core engine fuel is used in the exchanger at operating points where the ram burner is shut down. The heat exchanger tube sizing, however, was established on the basis of the original design concept and was based on the maximum heat flux occurring ahead of the nozzle throat. Thus it may be noted that the surface temperature achieved in the final design is well below the design limit of 700° F.

A transient temperature distribution for a typical tube in the region ahead of the throat is shown in Figure 58 for the tube design concept. This is based on a step change in gas temperature from 300° F to 3700° F and corresponds to a severe representation of an engine accel. These results were used to evaluate the mechanical integrity of the design. The corresponding steady-state temperature distribution is shown in Figure 59.

System 2 - (Ram Burner Liner Cooling Air Heat Exchanger)

In this heat exchanger design concept, the ram burner liner cooling air is cooled by use of two heat exchangers, one for the inner liner cooling air and the other for the outer liner cooling air. The design fuel surface temperature limit used in this configuration was set at 1000° F. The air side design pressure drops were set at 2% for the outer liner and 3.5% for the inner liner. The lower pressure drop set for the outer liner was designed to allow for the pressure drop in the struts located upstream of the outer liner heat exchanger. In order to preclude an increase in the engine outer shell diameter, the heat exchanger radial height was limited to one inch. A detailed description of the ram burner inner and outer cooling air heat exchanger is shown in Figure 60. The engine operating points used for the heat exchanger sizing were engine accel to satisfy the air side design pressure drop and the cruise operating conditions to satisfy the maximum fuel temperature limit. Pertinent engine operating conditions for these two points are shown in Table XL.

Table XL. Ramburner Liner Cooling Air Heat Exchangers Design Point Engine Operating Conditions.

100% Engine

| Operating Condition | Accel | Cruise |
|---|---|---|
| Ramburner Airflow, $W_{25}$ (pps) | 96.46 | 105.44 |
| Ramliner Cooling Airflow (pps) | 14.95 | 16.44 |
| Total Fuel Flow Rate (pph) | 22,450 | 10,426 |
| Heat Exchanger Inlet Pressure, $P_{25}$ (psia) | 51.99 | 51.68 |
| Heat Exchanger Inlet Air Temperature, $T_{25}$ (° F) | 1,932 | 1,932 |

The ram main burner fuel flow is the coolant source for these heat exchangers. The ram burner cooling air flow rate is 15.5% of $W_{25}$. Both the fuel and the air flow rates are divided between the inner liner and outer liner exchangers in proportion to their respective frontal areas. The ID for the

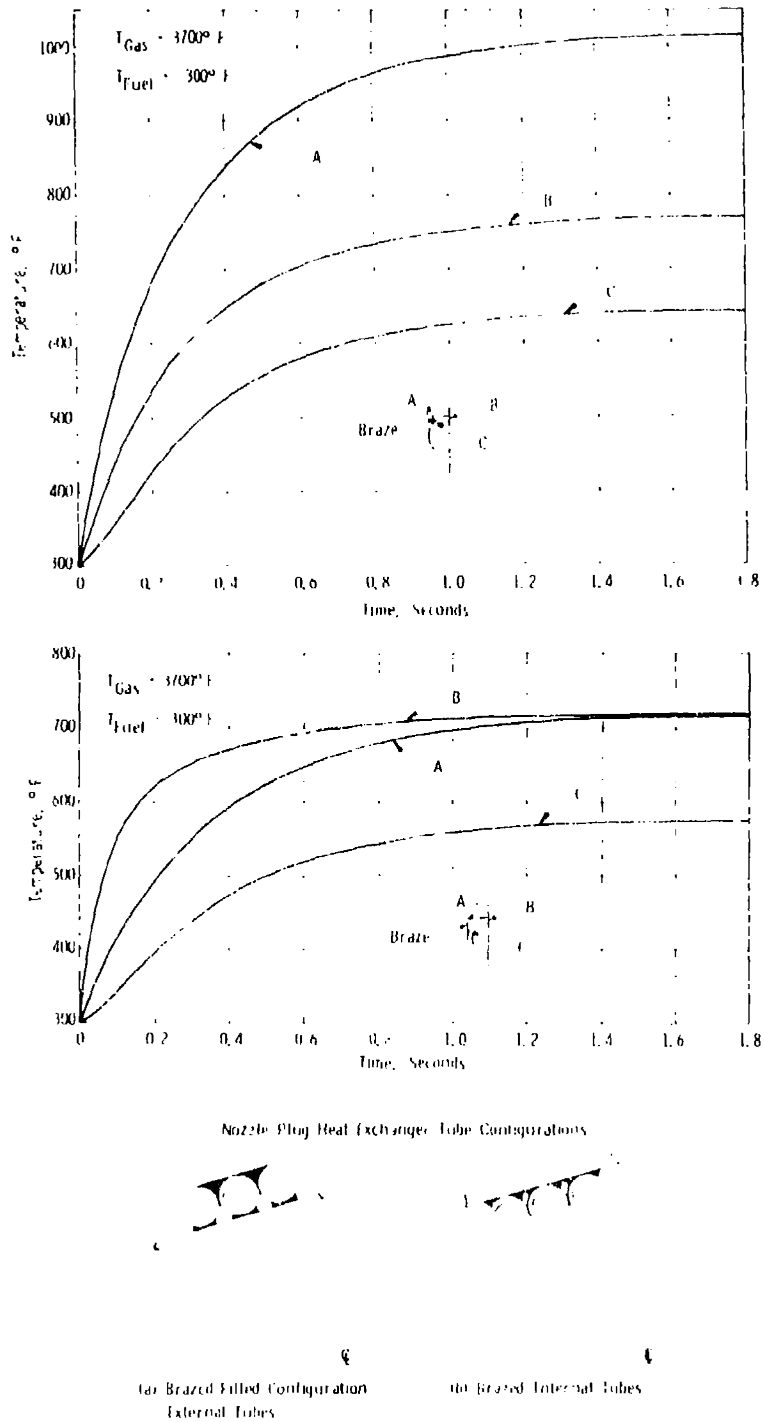
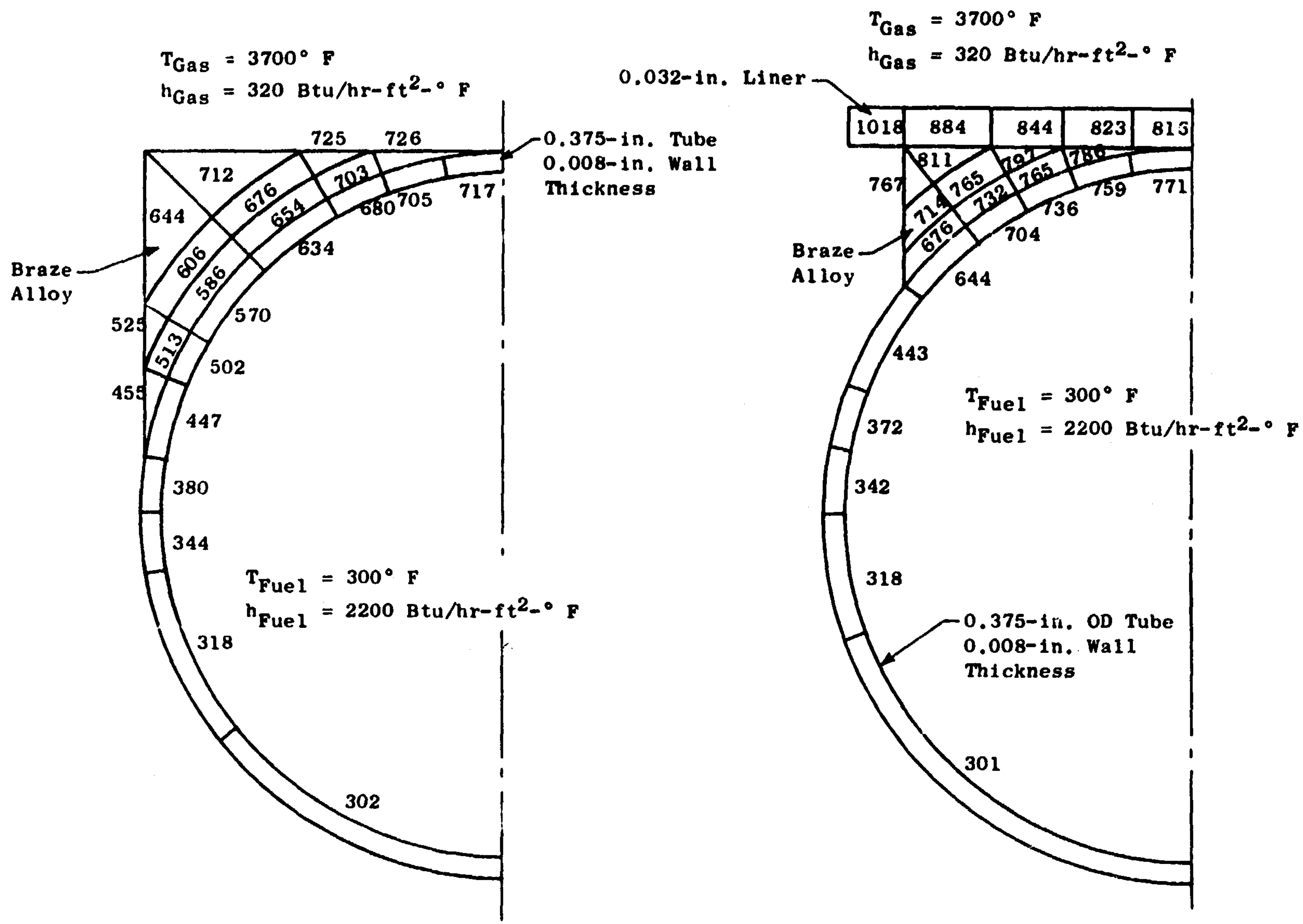



Figure 58. Exhaust Nozzle Plug Heat Exchanger Tube Temperatures for Step Change in Gas Temperature.




(a) Braze-Filled External Tubes

(b) Brazed Internal Tubes

**Figure 59. Exhaust Nozzle Plug Heat Exchanger Tube Steady-State Temperature Distribution.**

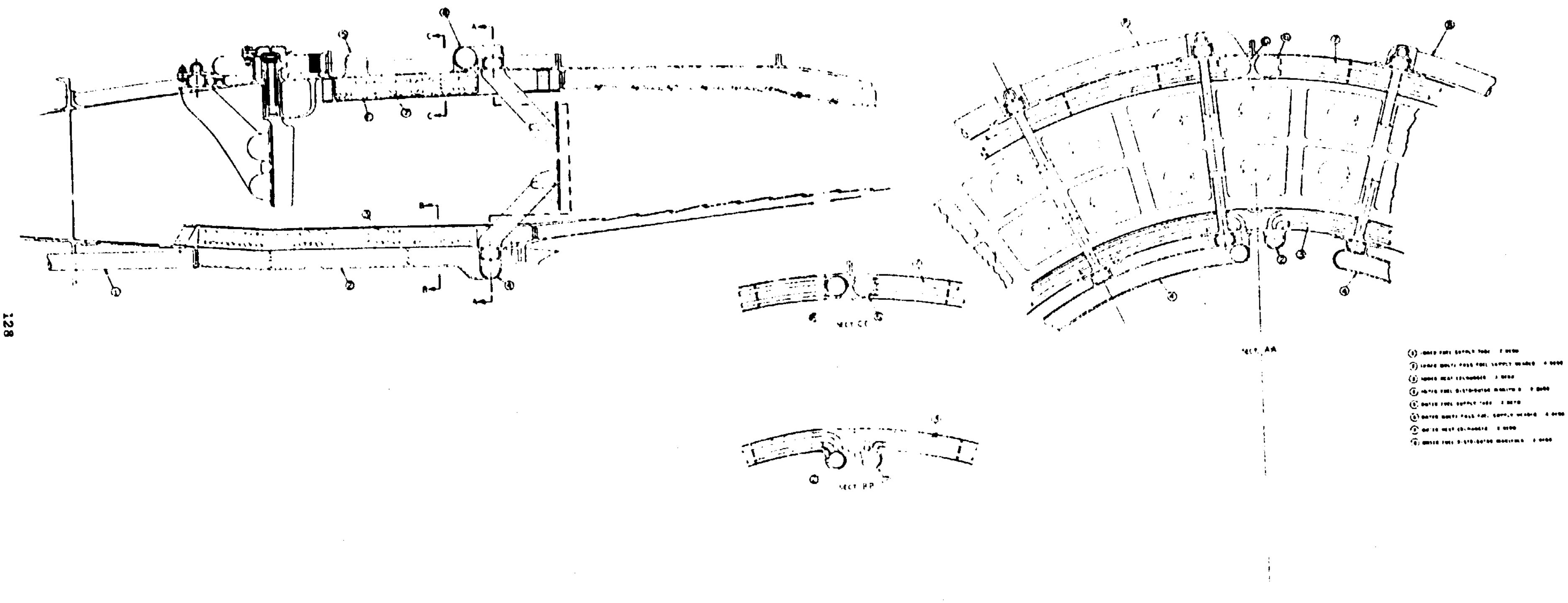


Figure 60. **GE14/FLITE-2A Ramburner Liner Cooling Air Heat Exchangers.**

inner liner heat exchanger is 33.4 inches and the ID for the outer liner heat exchanger is 47.6 inches. Correspondingly, the air flow rates used are 6.4% $W_{25}$ and 5.1% $W_{25}$ for inner and outer liner heat exchangers, respectively. The corresponding fuel flow rates are 58.7% and 41.3% of the ram main burner fuel flow. The design fuel inlet temperatures and pressures used were 300° F and 500 psia respectively. Since JP-7 fuel property data at temperatures above critical are presently unavailable, the property data used in this evaluation were based on elevated property data for JP-5 fuel as noted in Section III.

The configuration selected was an annular, bare tube cross flow four-pass heat exchanger, with the fuel flow inside the tubes and the air flow normal to the tubes. This configuration is similar to the design used in the Mission A studies. Multiple passes are used in order to increase the fuel side heat transfer coefficients by increasing the fuel velocity and thus minimize the fuel tube surface temperatures. This is accomplished by use of baffles in the heat exchanger fuel manifolds as illustrated in Figures 60 and 61.

The heat exchangers required to meet the specified operating conditions consist of tube arrays of 0.187-inch OD and 0.007-inch wall thickness. The heat exchangers are located in the ram duct immediately upstream of the main burner, with the inner and outer liner heat exchangers located in annular passages at the ID and OD of the ram duct respectively. The tubes are arranged circumferentially in 2 x 24 and 2 x 40 arrays for the respective outer and inner liner heat exchangers. The corresponding number of tubes per pass are 2 x 6 for the inner liner and 2 x 10 for the outer liner. The fuel is admitted into the tubes through an inlet manifold where the flow is split with one half of the fuel flowing circumferentially clockwise and the other half counterclockwise for an angular distance of 180° into the opposite or return manifold. This comprises one pass. The fuel is then returned, completing the second pass. This is repeated until the four passes are completed, at which point the fuel is discharged at the downstream end of the inlet manifold. Radial supports located 20 tube diameters (3.75 inches) apart are provided to minimize tube bending stresses and to assure that tube natural frequencies are above engine and vortex shedding excitation frequencies. The heat exchanger material is a high strength stainless steel alloy. The total estimated weight for the heat exchangers are 37.1 lb, of which 2.12 lb represents tubing weight with the balance being the weight of the manifolds and support structure. A detailed tabulation of heat exchanger configuration parameters is given in Table XLI.

The heat exchanger performance parameters for the inner and outer liner heat exchangers are summarized in Table XLII. It may be observed that the coolant temperature reductions obtained for the inner liner heat exchangers are 511° F and 382° F at accel and cruise operating conditions, respectively. The corresponding temperature reductions obtained for the outer liner heat exchanger are 366° F and 297° F. The reason for this difference is the lower air side pressure drop limit set for the outer liner heat exchanger. Thus, the average coolant temperature reduction is 420° F at the accel operating condition and 332° F at cruise. It may be further noted that the maximum fuel temperature obtained is 940° F and the maximum surface temperature is 970° F. Both of these values correspond to the inner liner heat exchanger and occur at the cruise operating condition.

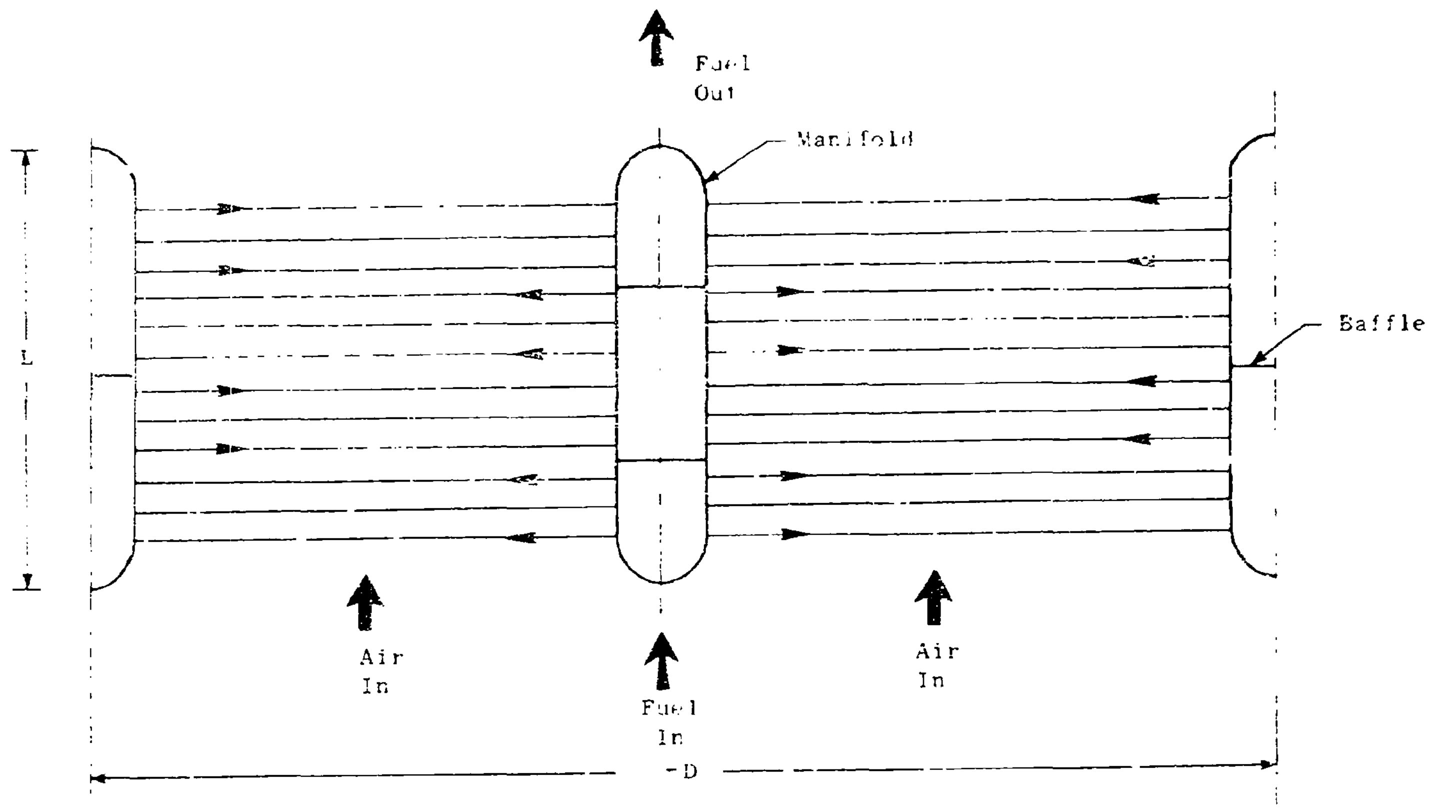



Figure 61. Schematic Diagram of 4-Pass Cross Flow Heat Exchanger.

Table XLI. Ramburner Liner Cooling Air Heat Exchangers Design Summary.

100% Engine

| | Inner Liner | Outer Liner |
|---|---|---|
| Tube OD (in) | 0.187 | 0.107 |
| Tube Wall Thickness (in) | 0.007 | 0.007 |
| Transverse Spacing (in) | 0.488 | 0.496 |
| Axial Spacing (in) | 0.235 | 0.235 |
| Axial Length (in) | 12.03 | 6.39 |
| Number of Axial Tube Rows | 48 | 24 |
| Number of Transverse Tube Rows | 2 | 2 |
| Number of Headers | 2 | 2 |
| Number of Fuel Passes | 4 | 4 |
| Annular Duct ID (in) | 33.40 | 47.60 |
| Annular Duct OD (in) | 35.35 | 49.58 |
| External Heat Transfer Area ($ft^2$) | 42.40 | 29.97 |
| Heat Exchanger Volume ($in^3$) | 1,268.0 | 967.7 |
| Tubing Weight (lb) | 12.40 | 8.80 |
| Header Weight (lb) | 6.40 | 3.00 |
| Radial Support Weight (lb) | 3.50 | 3.00 |
| Total Weight (lb) | 22.30 | 14.80 |

Table XLII. Ramburner Liner Cooling Air Heat Exchangers Performance Summary.

| Heat Exchanger | Inner Liner | | Outer Liner | |
|---|---|---|---|---|
| Operating Point | Accel | End of Cruise | Accel | End of Cruise |
| Fuel Flow Rate (pph) | 9,288 | 4,320 | 13,176 | 6120 |
| Air Flow Rate (pps) | 6.16 | 6.75 | 8.77 | 9.33 |
| Inlet Fuel Temperature (° F) | 300 | 300 | 300 | 300 |
| Inlet Air Temperature (° F) | 1,472 | 1,472 | 1,472 | 1,472 |
| Inlet Fuel Pressure (psia) | 500 | 500 | 500 | 500 |
| Inlet Air Pressure (psia) | 51.99 | 51.68 | 51.99 | 51.68 |
| ΔT Fuel (° F) | 415.6 | 639.7 | 327.2 | 521.7 |
| ΔT Air (° F) | 510.8 | 382.0 | 366.4 | 296.6 |
| ΔP/P Air (%) | 2.70 | 3.50 | 1.67 | 1.98 |
| ΔP Fuel (psia) | 2.96 | 1.02 | 26.50 | 7.05 |
| Exit Mach No. | 0.077 | 0.089 | 0.0785 | 0.0862 |
| Effectiveness | 0.436 | 0.546 | 0.313 | 0.445 |
| Max. Fuel Temperature (° F) | 716 | 940 | 627 | 822 |
| Max. Surface Temperature (° F) | 754 | 970 | 665 | 857 |
| Fuel Residence Time (sec) | 2.0 | 3.1 | 1.1 | 2.0 |

Mission B Engine Performance

The GE14/FLITE-2A engine was resized for a series of candidate engines for evaluating fuel type, fuel temperature, and cooling concepts in five Mission B studies. The engines that were resized are shown in Table XLIII and show that the engines used in Studies 3 and 4 were done in steps to permit fuel type, fuel temperature, and cooling concept to be evaluated as individual deltas.

The GE14/FLITE-2A engine performance calculated for the five Mission B studies represents the maximum obtainable from an increase in engine inlet fuel temperature in that it assumes the indicated interface fuel temperatures are applicable during the entire mission. From this performance the following points were noted:

a) Increasing the energy level of the system, through the fuel heating value or enthalpy, provides improved levels of engine performance.

b) Fuel-cooled turbojet plug nozzle provides improved engine performance only during turbojet operation.

c) Relatively small effects on engine performance are shown by fuel type, fuel temperature, and cooling concepts

B. Thermal Analysis

B.1 Study 1

Figure 62 shows the fluid system schematic for Mission B/Study 1. This study specified the use of JP-4/5/8 class of fuels at a maximum aircraft/engine interface fuel temperature of 150° F with each of the candidate lubricant/hydraulic fluids.

The design of the GE14/FLITE-2B fuel delivery system remained the same as that defined for the baseline GE14/FLITE-2A engine. Furthermore, restricting the maximum inlet fuel temperature to 150° F would permit the use of JP-4 fuel with little system penalty. As previously noted for the baseline, the GE14/FLITE-2B fuel delivery system incorporates the following features:

- Fuel recirculation to the aircraft main feed tank during ramjet idle descent.

- Recirculating temperature dependent manifold cooling flows for the core, preburner and main burner fuel lines when the respective burners are not in operation.

- Main engine control servo leakage being supplied directly from the pumps, bypassing the fuel/oil and fuel/hydraulic heat exchangers.

Table XLIII. Mission B Engine Candidates.

| Study | Fuel Type | Fuel Temp.,°F | Cooling | Comments |
|---|---|---|---|---|
| Baseline | JP-5 | 59 | | Base |
| 1 | JP-5 | 150 | Baseline | Delta effect in fuel enthalpy |
| 2 | JP-5 | 250 | Baseline | Additional delta effect in fuel enthalpy. |
| 3 | JP-7 | 59 | Baseline | Delta effect in fuel heating value. |
| | | 250 | Baseline | Delta effect in fuel heating value and enthalpy. |
| | | | Ramburner liner cooler | Delta effect in fuel heating value and enthalpy plus reduced ramburner liner cooling air |
| | | | Plug nozzle | Delta effect in fuel heating value and enthalpy plus reduced turbojet nozzle cooling air |
| 4 | JP-7 | 35[illegible] | Baseline | Delta effect in fuel heating |
| | | | Ramburner liner cooler | Delta effect in fuel heating value and enthalpy plus reduced ramburner liner cooling air |
| 5 | JP-7 | 100 | Ramburner liner cooler | Delta effect in fuel heating value and enthalpy plus reduced ramburner liner cooling air (precooled fuel). |

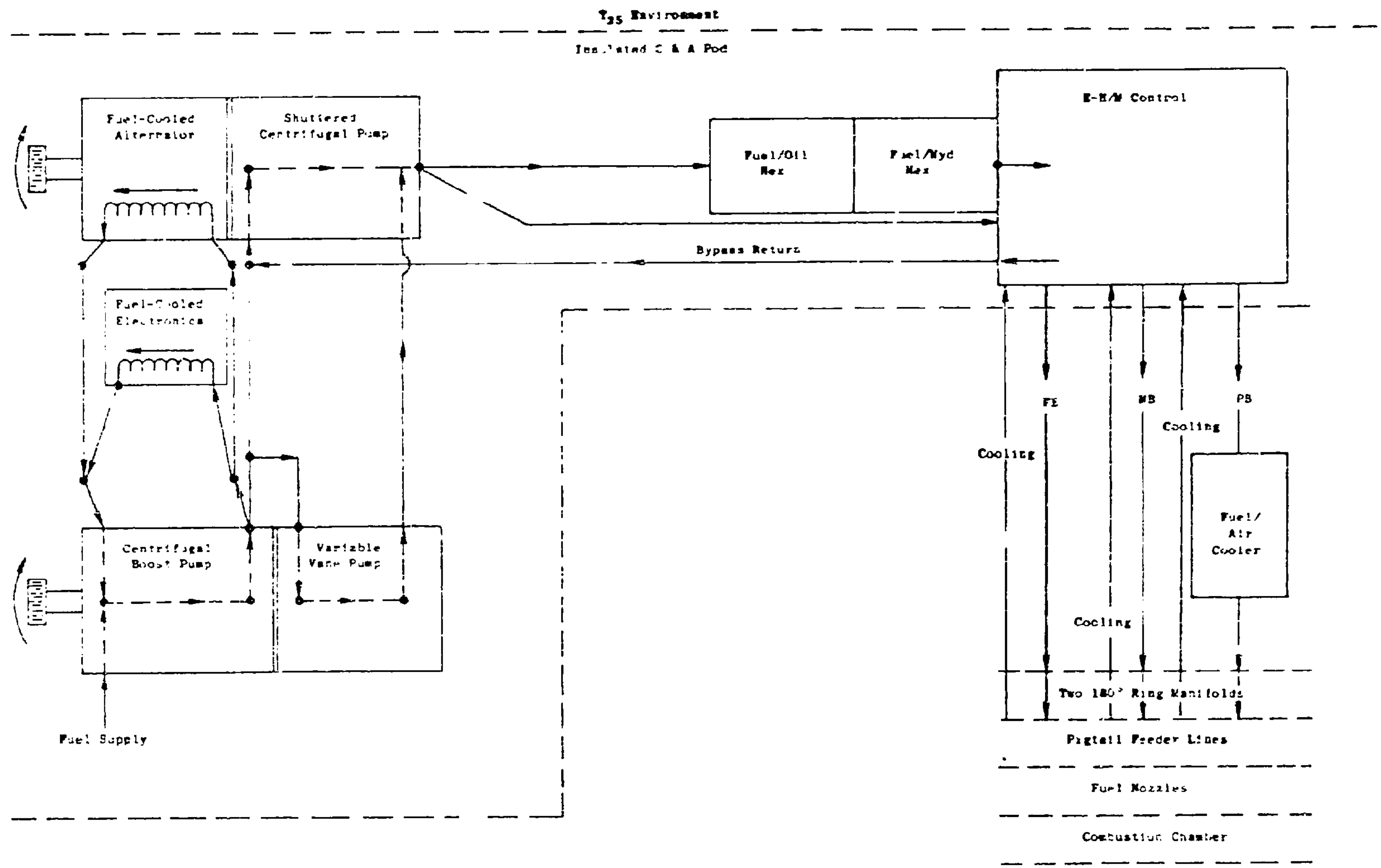



Figure 62. Mission 3/1 Study 1 Fluid System Schematic.

The definition of the GE14/FLITE-2B fluid power system remained the same as that defined for the baseline. A summary of the fuel and fluid power system weights for each of the four candidate lubricants is listed in Table XLIV.

In the GE14/FLITE-2B, engine volumetric oil flow was allowed to remain the same for each lubricant. System optimization with the higher temperature lubricants was accomplished by the removal of heat shields and insulation and by scaling of the sump cooling air fuel/air cooler that is located in the ram preburner fuel line downstream of the main engine control. The cooler requirements for each of the four lubricants is listed in Table XLV. No cooling of the sump air is required for either the polyphenyl ether or the perfluorinated polyether lubricants nor is there sump air cooling required for any of the lubricants during either idle-descent. The elevated oxidative stability temperature of the perfluorinated polyether permitted the removal of heat shields in both the forward and aft sumps. However, the high vapor pressure of this fluid also required the use of nonvented sumps. In these sump designs, carbon seals are used as oil seals and new labyrinth air seals are added with the intermediate cavities overboard to ambient pressure.

Lubrication system weight changes for the four lubricants is presented in Table XLVI. A summary of the total engine weight increments due to the use of these fluids is given in Table XLVII.

Using the GE14 thermal model, Mission B was executed for each of the candidate lubricants for JP-5 fuel at a maximum inlet temperature of 150° F. The thermal profiles for each lubricant are shown in Figures 63 to 66.

The critical phase for heat sink utilization is during the ramjet idle-descent portion of the mission. During this phase, fuel recirculation to the aircraft main feed tank is necessary to provide enough fuel to maintain system fluid temperatures within maximum permissible limits. A summary of system performance for each lubricant during ramjet idle-descent is shown in Tables XLVIII to LI. As can be noted from these tables maximum recirculation fuel flow rates vary from 9,276 pph for MIL-L-27502 to 7,759 pph for perfluorinated polyether with an associated fuel weight increment range of from 388 lb to 324 lb, respectively. It can be further noted that the fuel temperature exceeds 325° F in the ram main burner and preburner lines when these burners are in operation during ramjet idle-descent. These overtemperature conditions are of short duration and are deemed tolerable for the JP-5 fuel, but it should be noted that a maximum fuel temperature of 325° F can no longer be guaranteed over the entire mission for a Mach 4+ interceptor.

B.2 Study 2

Mission B/Study 2 involves the use of the four lubricant/hydraulic fluids with JP5/8 fuel at a maximum inlet temperature of 250° F.

A schematic of the GE14/FLITE-2C fluid system is shown in Figure 67. The functions of the fuel delivery, lubrication and fluid power systems are similar to those described for Mission B/Study 1. System weight changes remain the same as defined for Study 1 and are itemized in Table LII.

Table XLIV. GE14/FLITE-2B Fuel and Fluid Power System Weight Increments for the Candidate Hydraulic Fluids.

201.5% Engine

| Fuel and FPS Components (1) | Fuel System (ΔWt-lb) Base JP-5 at 200° F | FLITE-2C JP-5 at 250° F | Fluid Power System (ΔWt-lb) Base MIL-L 27502 | GE14/FLITE-2C MIL-L 27502 | 500° F Ester | Polyphenyl Ether | Perfluor. Polyether |
|---|---|---|---|---|---|---|---|
| Fuel System | Base | Same | | | | | |
| FPS | | | | | | | |
| Fluid (Wt-lb) 328 $in^3$ at 80° F | | | 11.6 | 11.6 | 11.6 | 14.2 | 22.5 |
| Integral Hyd. Pump (hidu-minimum≤450° F) | | | 34.2 | 34.2 | 50.9 | 50.9 | 55.8 |
| Hyd. Reservoir (T≤550° F) | | | 38.0 | 38.0 | 38.0 | 38.0 | 52.0 |
| Ti Piping & Insulation (T≤550° F) | | | 30.4 | 30.4 | 30.4 | 30.4 | 42.0 |
| Other Hyd. Components (T≤550° F) | | | 26.5 | 26.5 | 26.5 | 26.5 | 33.8 |
| 16-$A_8$ Act. (Titanium) | | | 27.0 | 27.0 | 27.0 | 27.0 | 45.8 |
| 16-$A_{29}$ Act. (Titanium) | | | 63.2 | 63.2 | 63.2 | 63.2 | 104.6 |
| 16-$A_{28}$ Act. (Titanium) | | | 32.2 | 32.2 | 32.2 | 32.2 | 54.0 |
| 2-$A_4$ Act. (Titanium) | | | 6.2 | 6.2 | 6.2 | 6.2 | 10.3 |
| 2-$A_{25}$ Act. (Titanium) | | | 6.2 | 6.2 | 6.2 | 6.2 | 10.3 |
| 2-VSV Act. (Titanium) | | | 6.2 | 6.2 | 6.2 | 6.2 | 10.3 |
| ΔWt. Penalty (lb) | Base | Same | Base | Same | +16.7 | +19.3 | +159.7 |

(1) - Only components having weight changes are listed.

## Table XLV. GE14/FLITE-2B Fuel/Air Cooler Requirements

<u>201.5% Engine</u>

Design Point Flight Conditions

WAIR = 0.008 x W2C = 2.84 pps

| | A | B | C | D |
|---|---|---|---|---|
| Q (Btu/min) | 2,940 | 1,033 | 0 | 0 |
| $T_{A_1}$ (° F) | 1,029 | 1,029 | 1,029 | 1,029 |
| $T_{A_1}$ (° F) | 967 | 1,007 | 1,029 | 1,029 |
| $\Delta T_{air}$ (° F) | 62 | 22 | 0 | 0 |

A = MIL-L-27502
B = 500° F Ester
C = Polyphenyl Ether
D = Perfluorinated Polyether
$T_{A_1}$ = Cooler Air Inlet Temperature
$T_{A_2}$ = Cooler Discharge Temperature

## Table XLVI. GE14/FLITE-2B Lubrication System Weight (Variable Items).

<u>201.5% Engine</u>

| Component | MIL-L-27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|
| Fuel/Air Cooler (lb) | 16.61 | 13.36 | 0 | 0 |
| Fuel/Oil Cooler (lb) | 9.64 | 7.13 | 5.24 | 5.24 |
| Fuel/Hyd. Cooler (lb) | 9.64 | 7.13 | 5.24 | 5.24 |
| Lube Tank (lb) | 15.60 | 17.10 | 17.40 | 15.90 |
| "A" Sump Heat Shield (lb) | 0 | 0 | 0 | -1.77 |
| "B" Sump Heat Shield (lb) | 0 | 0 | 0 | -1.27 |
| Nonvented Sump Hardware (lb) | 0 | 0 | 0 | 22. |
| Fluid Weight (lb) | 19.80 | 23.90 | 30.00 | 39.7 |
| Total Weight (lb) | 71.29 | 68.62 | 57.88 | 85.59 |
| Delta Weight (lb) | 0 | -2.67 | -13.41 | +14.30 |

Table XLVII. GE14/FLITE-2B Engine Weight Changes for the Candidate Lubricants.

| | MIL-L-27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|
| | | 201.5% Engine | | |
| Fuel System (lb) | 0 | 0 | 0 | 0 |
| Fluid Power (lb) | 0 | +16.7 | +19.3 | +159.7 |
| Lubrication System (lb) | 0 | -2.67 | -13.41 | +14.30 |
| Delta Weight (lb) | 0 | +14.03 | +5.89 | +174.00 |
| | | 100% Engine | | |
| Fuel System (lb) | 0 | 0 | 0 | 0 |
| Fluid Power (lb) | 0 | +12.07 | +13.95 | +27.70 |
| Lubrication System (lb) | 0 | -1.50 | -9.20 | +10.46 |
| Delta Weight (lb) | 0 | +10.57 | +4.75 | +125.85 |

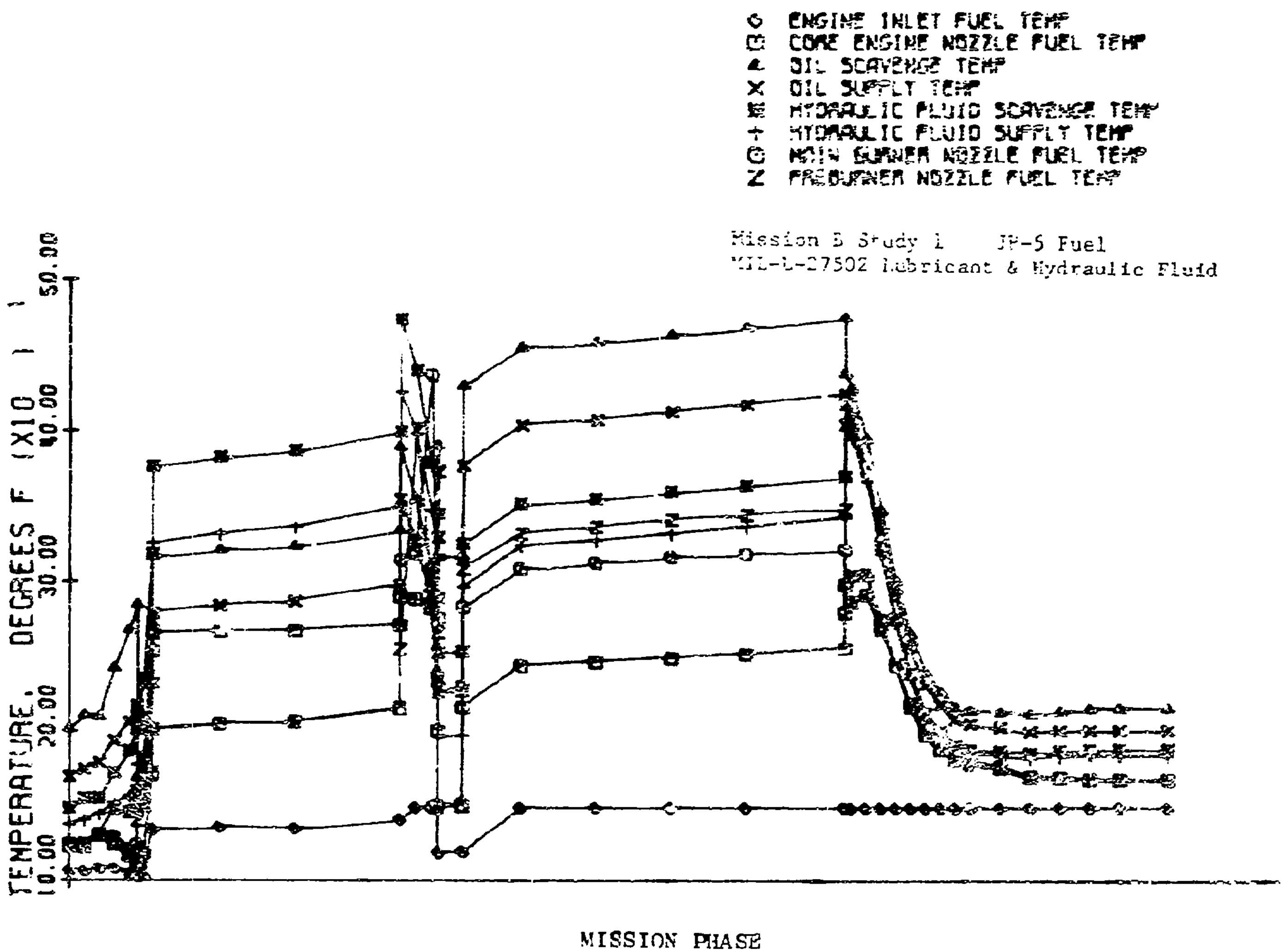



Figure 63. GE14/FLITE-2B Thermal Profiles, MIL-L-27502.

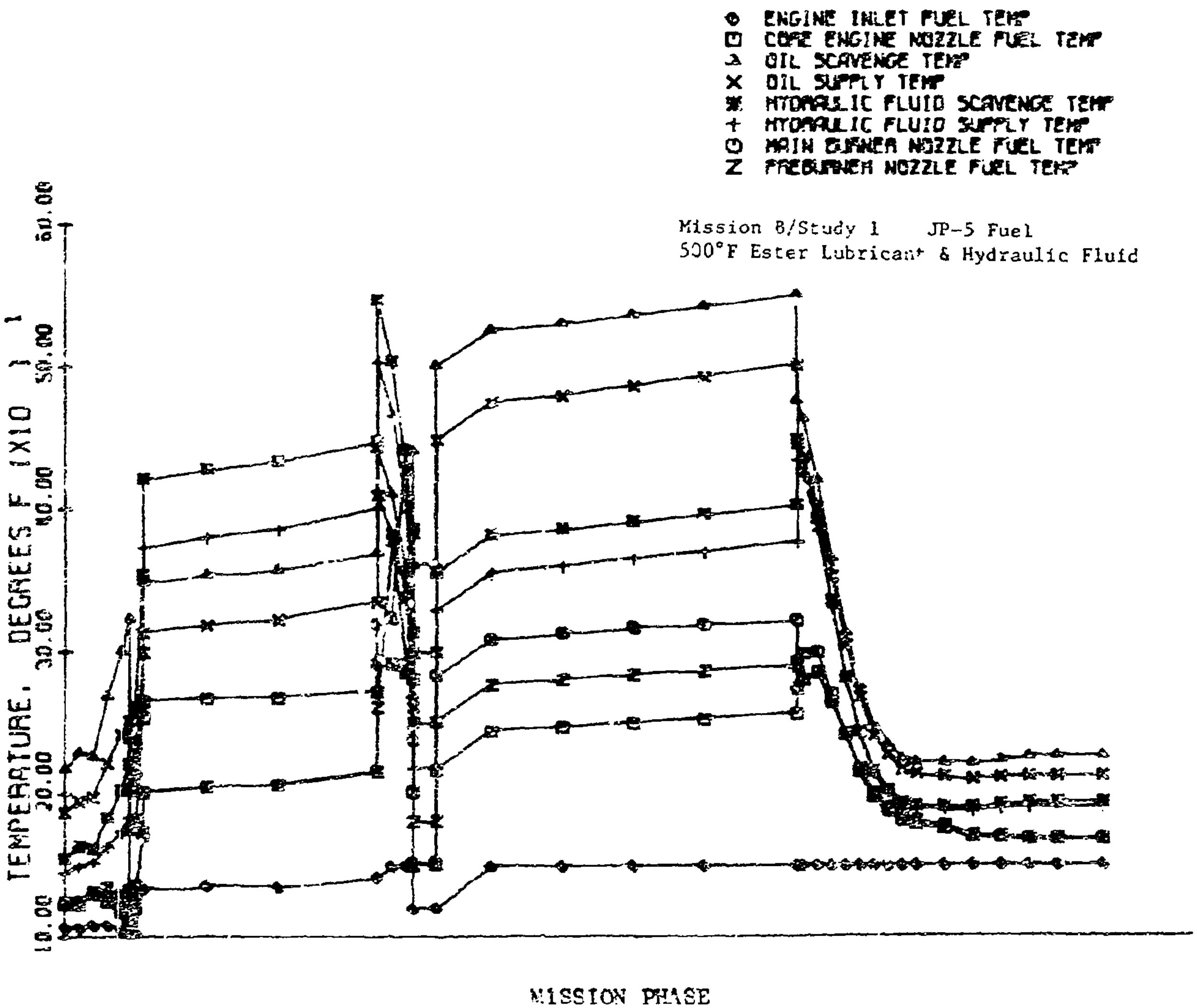



Figure 64. GE14/FLITE-2B Thermal Profiles, 500° F Ester.

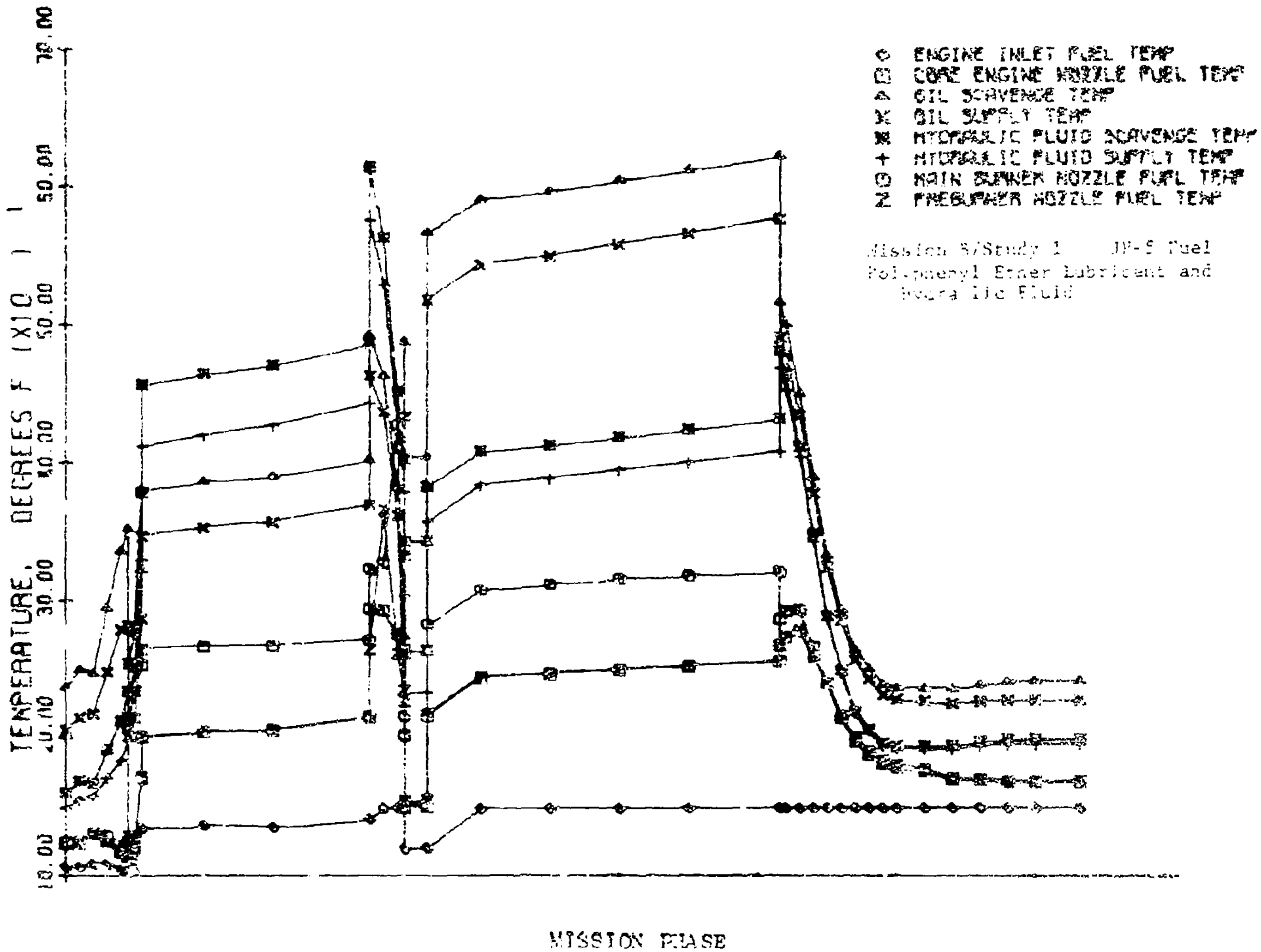



Figure 65. GE14/FLITE-2B Thermal Profiles. Polyphenyl Ether.

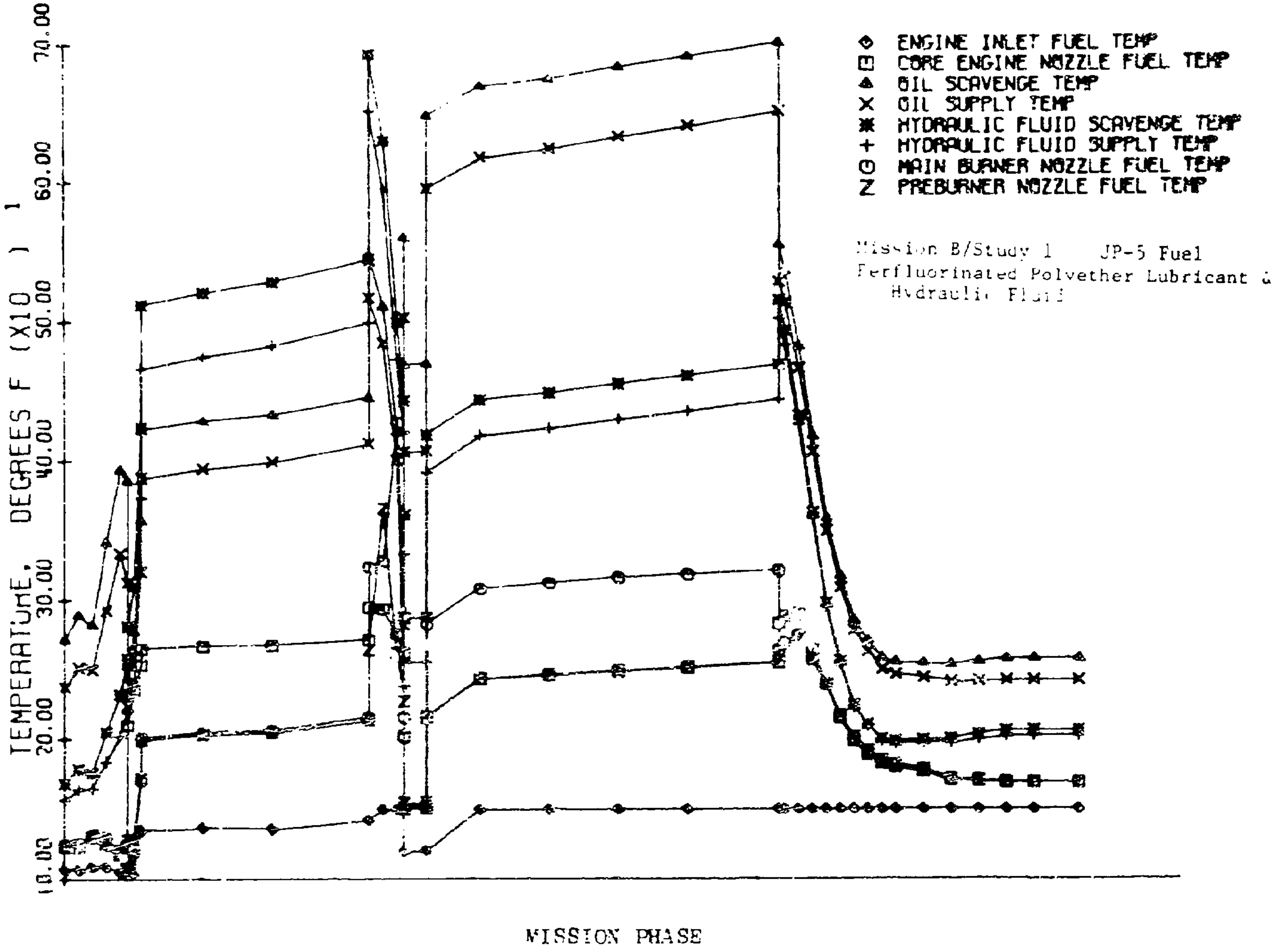



Figure 66, GE14/FLITE-2B Thermal Profiles, Perfluorinated Polyether.

Table XLVIII. GE14/FLITE-2B Ramjet Idle-Descent Summary, MIL-L-27502.

201.5% Engine

| Time Minutes | 0.00 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|
| TFO (° F) | 150 | 150 | 150 | 150 | 150 |
| TF7 (° F) | 247 | 244 | 234 | 224 | 191 |
| TF14C (° F) | --- | --- | --- | --- | 202 |
| TF14P (° F) | --- | 403 | 304 | 268 | 374 |
| TF14M (° F) | 316 | 320 | 439 | --- | --- |
| TO2 (° F) | 355 | 328 | 291 | 234 | 330 |
| TH2 (° F) | 350 | 427 | 399 | 348 | 258 |
| WREC (pph) | 9,180 | 9,188 | 9,215 | 9,241 | 9,276 |

Recirculation Fuel Weight = 388 pounds

Table XLIX. GE14/FLITE-2B Ramjet Idle-Descent Summary, 500° F Ester.

201.5% Engine

| Time Minutes | 0.00 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|
| TFO (° F) | 150 | 150 | 150 | 150 | 150 |
| TF7 (° F) | 252 | 250 | 239 | 229 | 192 |
| TF14C (° F) | --- | --- | --- | --- | 203 |
| TF14P (° F) | --- | 378 | 292 | 262 | 281 |
| TF14M (° F) | 321 | 325 | 443 | --- | --- |
| TO2 (° F) | 409 | 382 | 338 | 261 | 382 |
| TH2 (° F) | 503 | 465 | 398 | 361 | 283 |
| WREC (pph) | 8,410 | 8 416 | 8,440 | 8,465 | 8,508 |

Recirculation Fuel Weight = 355 pounds

Table L. GE14/FLITE-2B Ramjet Idle-Descent Summary, Polyphenyl Ether.

201.5% Engine

| Time Minutes | 0.00 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|
| TFO (° F) | 150 | 150 | 150 | 150 | 150 |
| TF7 (° F) | 256 | 254 | 218 | 208 | 193 |
| TF14C (° F) | --- | --- | --- | --- | 204 |
| TF14P (° F) | --- | 367 | 263 | 236 | 227 |
| TF14M (° F) | 324 | 329 | 428 | --- | --- |
| T02 (° F) | 463 | 437 | 362 | 265 | 433 |
| TH2 (° F) | 576 | 529 | 424 | 380 | [illegible]04 |
| WREC (pph) | 7,800 | 7,805 | 7,788 | 7,885 | 7,899 |

Recirculation Fuel Weight = 330 pounds

Table LI. GE14/FLITE-2B Ramjet Idle-Descent Summary, Perfluorinated Polyether.

201.5% Engine

| Time Minutes | 0.00 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|
| TFO (° F) | 150 | 150 | 150 | 150 | 150 |
| TF7 (° F) | 256 | 254 | 218 | 208 | [illegible] |
| TF14C (° F) | --- | -- | --- | --- | 204 |
| TF14P (° F) | --- | 366 | 262 | 235 | 227 |
| TF14M (° F) | 324 | 329 | 428 | --- | --- |
| T02 (° F) | 517 | 484 | 400 | 282 | 503 |
| TH2 (° F) | 651 | 594 | 472 | 420 | 332 |
| WREC (pph) | 7,655 | 7,659 | 7,737 | ,759 | 7,751 |

Recirculation Fuel Weight = 324 pounds

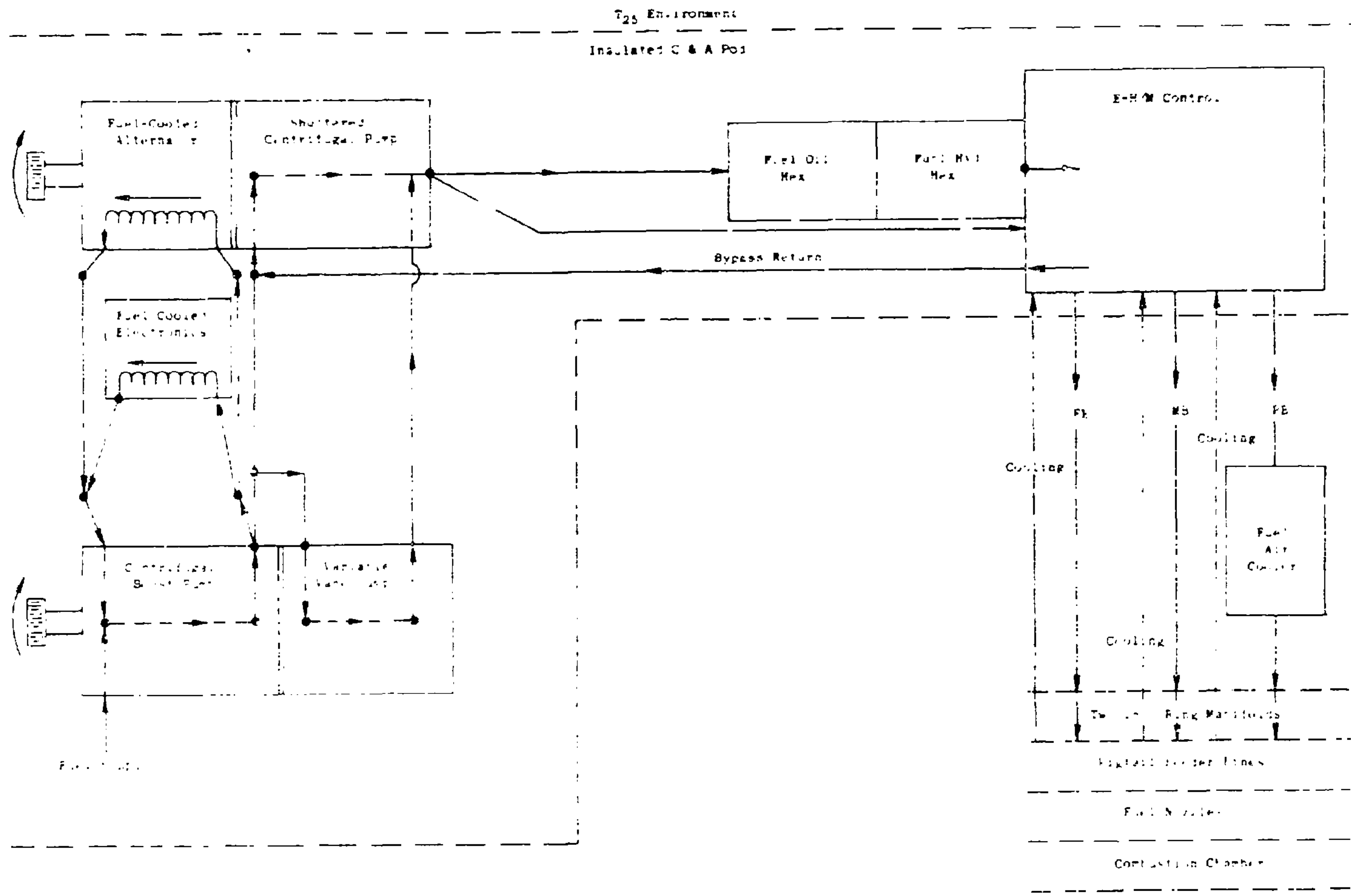



Figure 67. Mission B/Study 2 Fluid System Schematic.

Table LII. GE14/FLITE-2C Engine Weight Changes for the Candidate Lubricants.

| | MIL-L 27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|
| | | 201.5% Engine | | |
| Fuel System (lb) | 0 | 0 | 0 | 0 |
| Fluid Power (lb) | 0 | +16.7 | +19.3 | +159.7 |
| Lubrication System (lb) | 0 | -2.67 | -13.41 | +14.30 |
| Delta Weight (lb) | 0 | +14.03 | +5.89 | +174.00 |
| | | 100% Engine | | |
| Fuel System (lb) | 0 | 0 | 0 | 0 |
| Fluid Power (lb) | 0 | +12.07 | +13.95 | +115.39 |
| Lubrication System (lb) | 0 | -1.50 | -9.20 | +10.46 |
| Delta Weight (lb) | 0 | +10.57 | +4.75 | +1125.85 |

Using the GE14 thermal model, computer runs were executed for each fluid, the results of which are shown in Figures 68 to 71. The idle-descent summaries are given in Tables LIII to LVI. Although the recirculation fuel flow rates for the ramjet idle-descent are similar to those listed for Study 1, it can be seen that the fuel inlet temperatures to the engine have been reduced substantially below the 250° F maximum level. This reduction was the result of an iterative process to properly match the engine fluid system and the aircraft ECS heat load requirements. With a 250° F inlet temperature to the engine, the quantities of engine fuel recirculation to the aircraft reach levels where the aircraft ECS heat load is insufficient to provide the 250° F interface temperature. As a result of this condition, the 250° F maximum temperature condition is reached only during the final idl -descent to sea level.

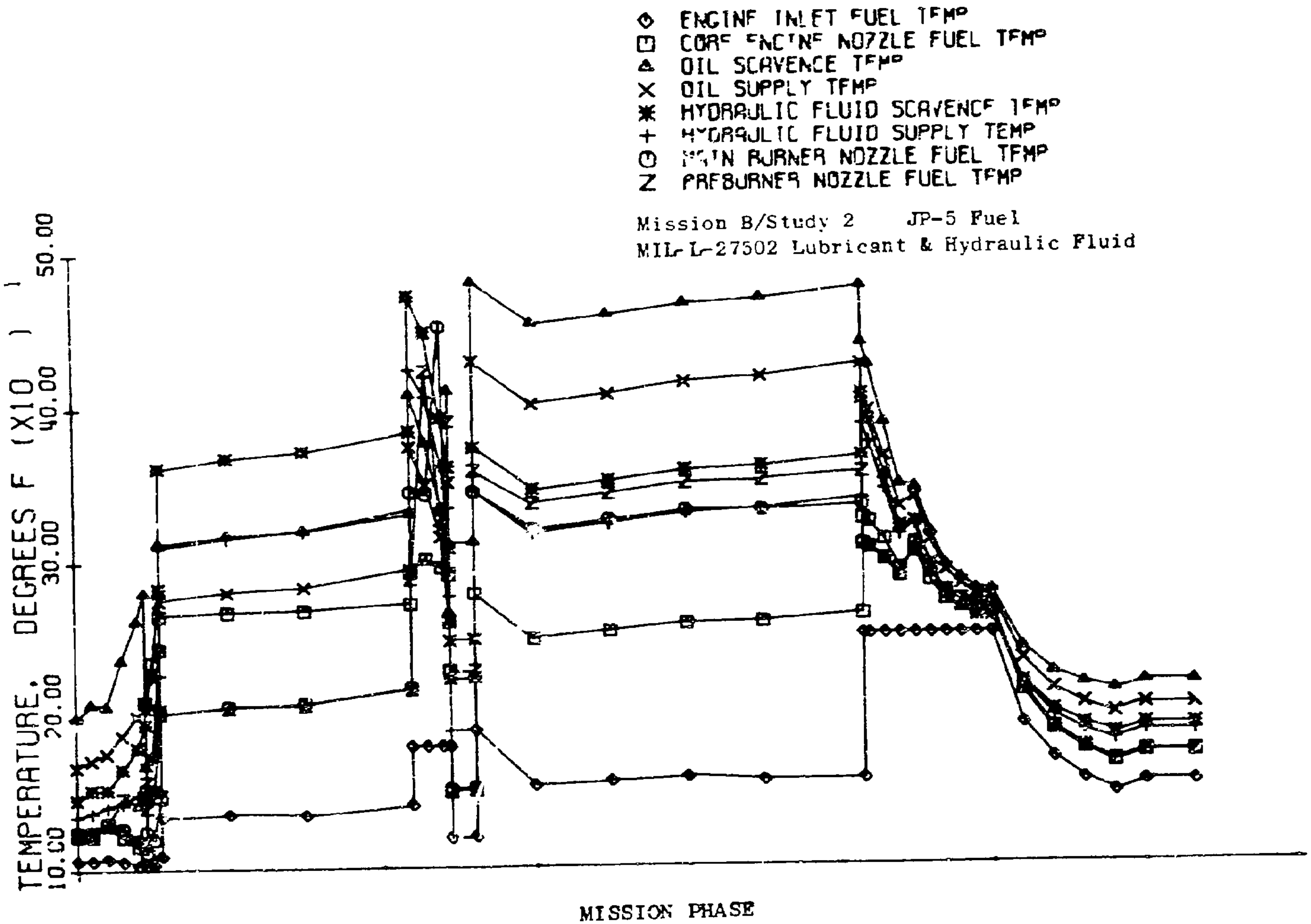



Figure 68. GE14/FLITE-2C Thermal Profiles, MIL-L-27502.

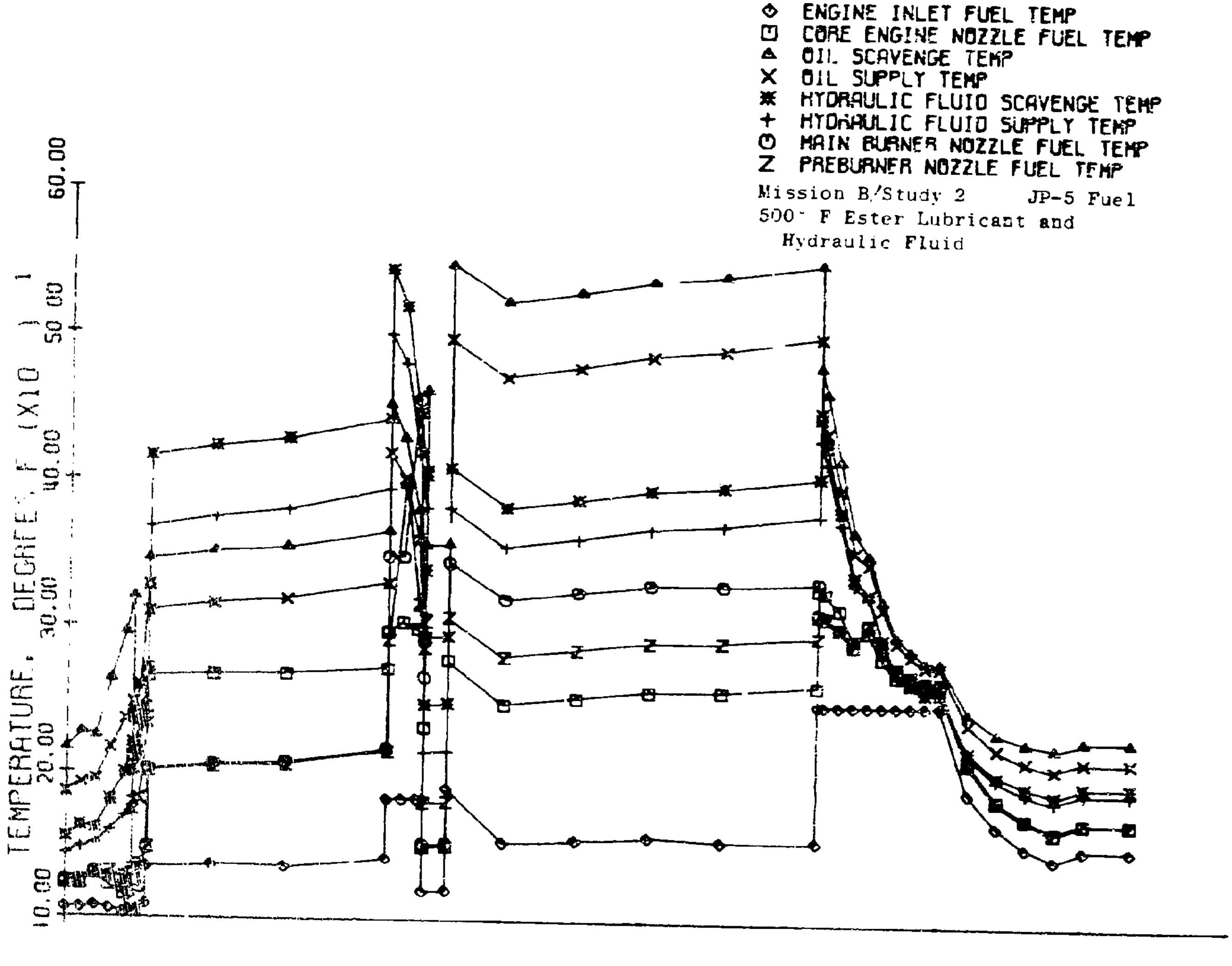



Figure 69. GE14/FLITE-2C Thermal Profiles, 500° F Ester.

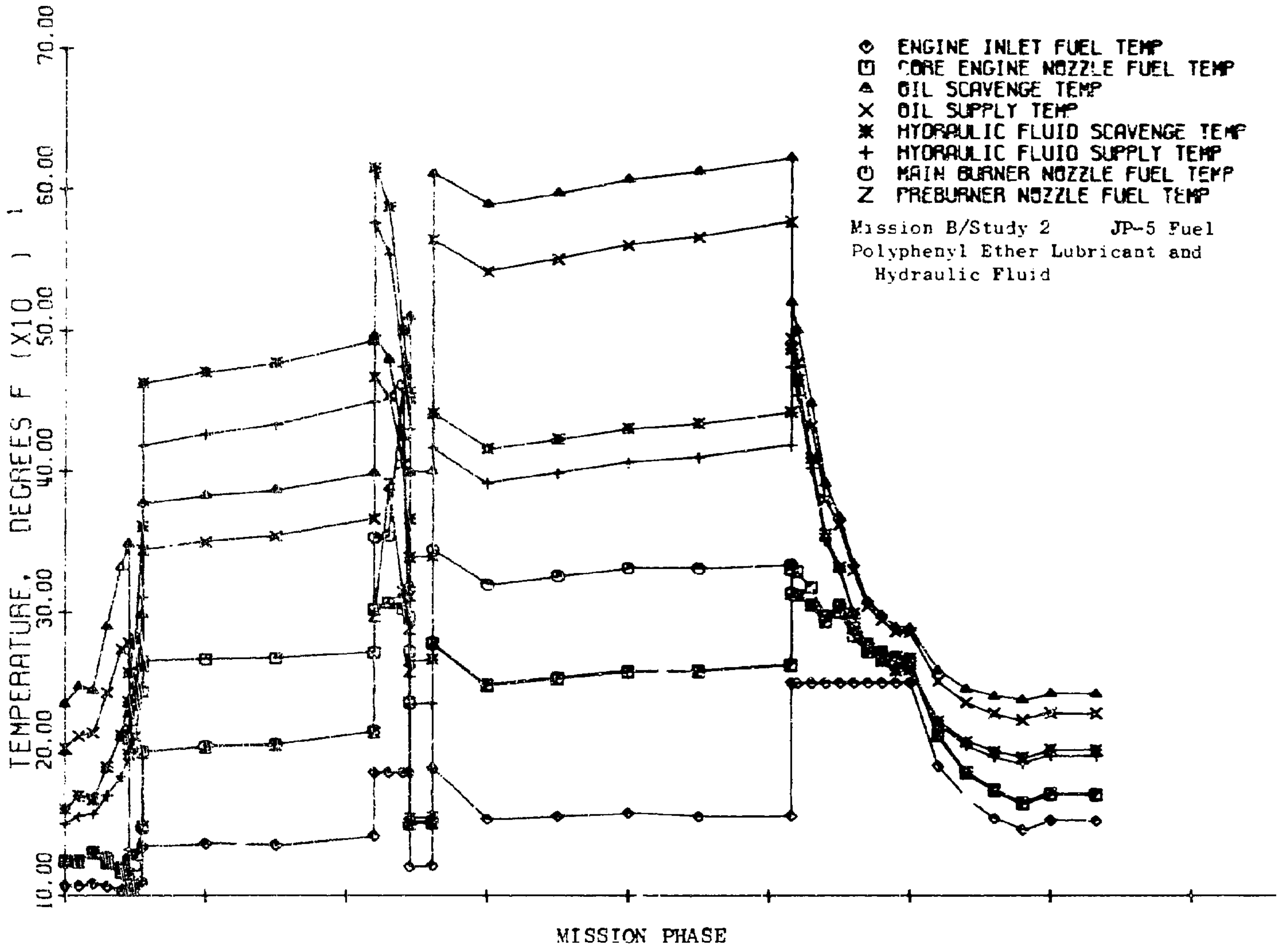



Figure 7[illegible]. GE14/FLITE-2C Thermal Profiles, Polyphenyl Ether.

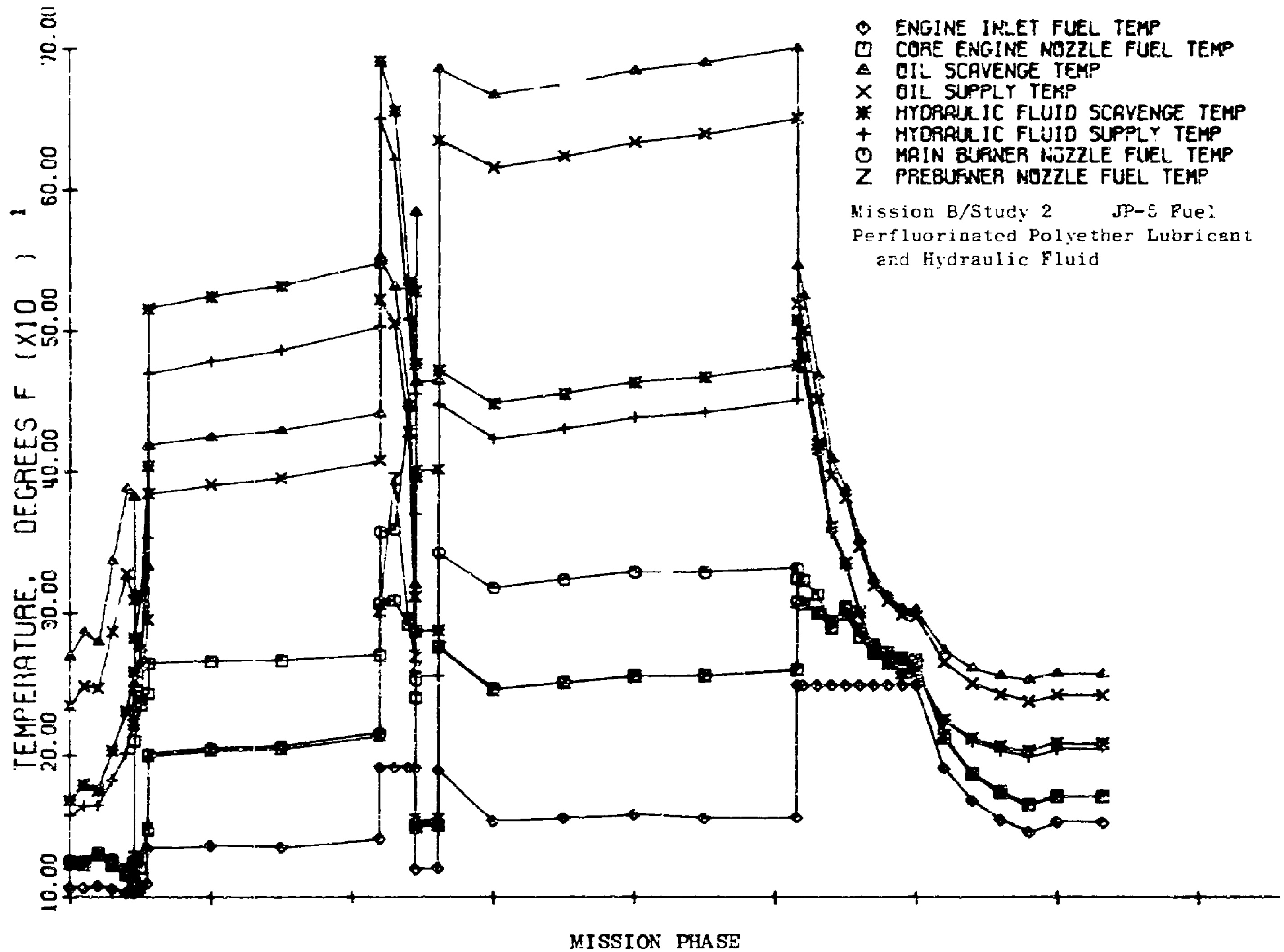



Figure 71. GE14/FLITE-2C Thermal Profiles, Perfluorinated Polyether.

Table LIII. GE14/FLITE-2C Idle-Descent Summary, MIL-L-27502.

(a) Ramjet Idle-Descent

201.5% Engine

| Time Minutes | 0.00 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|
| TFO (° F) | 180 | 180 | 180 | 180 | 180 |
| TF7 (° F) | 280 | 272 | 262 | 252 | 220 |
| TF14C (° F) | --- | --- | --- | --- | 231 |
| TF14P (° F) | --- | 424 | 328 | 292 | 391 |
| TF14M (° F) | 346 | 344 | 453 | --- | --- |
| TO2 (° F) | 374 | 350 | 316 | 260 | 351 |
| TH2 (° F) | 424 | 407 | 362 | 335 | 277 |
| WREC (pph) | 9,000 | 9,023 | 9,048 | 9,074 | 9,109 |

Recirculation Fuel Weight = 379 Pounds

(b) Idle-Descent to Sea level

201.5% Engine

| Time Minutes | 0.00 | 0.43 | 1.43 | 2.43 |
|---|---|---|---|---|
| TFO (° F) | 250 | 250 | 250 | 250 |
| TF7 (° F) | 304 | 302 | 294 | 283 |
| TF14C (° F) | 326 | 324 | 312 | 293 |
| TF14P (° F) | --- | --- | --- | --- |
| TF14M (° F) | --- | --- | --- | --- |
| TO2 (° F) | 405 | 395 | 365 | 332 |
| TH2 (° F) | 386 | 374 | 344 | 314 |
| WREC (pph) | 2,200 | 2,201 | 2,206 | 2,213 |

Recirculation Fuel Weight -89 Pounds

Table LIV. GE14/FLITE-2C Idle-Descent Summary, 500° F Ester.

(a) Ramjet Idle-Descent

201.5% Engine

| Time Minutes | 0.00 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|
| TFO (° F) | 183 | 183 | 183 | 183 | 183 |
| TF7 (° F) | 284 | 278 | 401 | 258 | 223 |
| TF14C (° F) | --- | --- | --- | --- | --- |
| TF14P (° F) | --- | 323 | 317 | 288 | 306 |
| TF14M (° F) | 350 | 349 | 457 | --- | --- |
| TO2 (° F) | 420 | 402 | 360 | 285 | 404 |
| TH2 (° F) | 500 | 480 | 418 | 382 | 310 |
| WREC (pph) | 8,500 | 8,517 | 8,540 | 8,566 | 8,606 |

Recirculation Fuel Weight = 358 Pounds

(b) Idle-Descent to Sea Level

201.5% Engine

| Time Minutes | 0.00 | 0.43 | 1.43 | 2.43 |
|---|---|---|---|---|
| TFO (° F) | 250 | 250 | 250 | 250 |
| TF7 (° F) | 304 | 302 | 292 | 280 |
| TF14C (° F) | 325 | 323 | 310 | 296 |
| TF14P (° F) | --- | --- | --- | --- |
| TF14M (° F) | --- | --- | --- | --- |
| TO2 (° F) | 440 | 430 | 387 | 355 |
| TH2 (° F) | 426 | 414 | 367 | 320 |
| WREC (pph) | 2,000 | 2,001 | 2,004 | 2,009 |

Recirculation Fuel Weight = 81 Pounds

Table LV. GE14/FLITE-2C Idle-Descent Summary, Polyphenyl Ether.

(a) Ramjet Idle-Descent

201.5% Engine

| Time Minutes | 0.00 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|
| TF0 (° F) | 187 | 187 | 187 | 187 | 187 |
| TF7 (° F) | 289 | 284 | 275 | 264 | 227 |
| TF14C (° F) | --- | --- | --- | --- | 238 |
| TF14P (° F) | --- | 392 | 315 | 289 | 259 |
| TF14M (° F) | 354 | 355 | 462 | --- | --- |
| T02 (° F) | 467 | 453 | 405 | 311 | 456 |
| TH2 (° F) | 576 | 553 | 474 | 430 | 339 |
| WREC (pph) | 8,000 | 8,013 | 8,034 | 8,058 | 8,102 |

Recirculation Fuel Weight = 337 Pounds

(b) Idle-Descent to Sea Level

201.5% Engine

| Time Minutes | 0.00 | 0.43 | 1.43 | 2.43 |
|---|---|---|---|---|
| TF0 (° F) | 250 | 250 | 250 | 250 |
| TF7 (° F) | 304 | 303 | 297 | 287 |
| TF14C (° F) | 325 | 323 | 313 | 294 |
| TF14P (° F) | --- | --- | --- | --- |
| TF14M (° F) | --- | --- | --- | --- |
| T02 (° F) | 486 | 467 | 418 | 364 |
| TH2 (° F) | 453 | 430 | 375 | 330 |
| WREC (pph) | 1,700 | 1,700 | 1,703 | 1,706 |

Recirculation Fuel Weight = 69 Pounds

Table LVI. GE14/FLITE-2C Idle-Descent Summary, Perfluorinated Polyether.

(a) Ramjet Idle-Descent

201.5% Engine

| Time Minutes | 0.00 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|
| TF0 (° F) | 192 | 192 | 192 | 192 | 192 |
| TF7 (° F) | 295 | 290 | 257 | 246 | 232 |
| TF14C (° F) | --- | --- | --- | --- | 243 |
| TF14P (° F) | --- | 397 | 298 | 271 | 264 |
| TF14M (° F) | 359 | 361 | 449 | --- | --- |
| TO2 (° F) | 523 | 506 | 429 | 312 | 529 |
| TH2 (° F) | 651 | 622 | 509 | 456 | 370 |
| WREC (pph) | 7,500 | 7,509 | 7,583 | 7,605 | 7,597 |

Recirculation Fuel Weight = 317 Pounds

(b) Idle-Descent to Sea Level

201.5% Engine

| Time Minutes | 0.00 | 0.43 | 1.43 | 2.43 |
|---|---|---|---|---|
| TF0 (° F) | 250 | 250 | 250 | 250 |
| TF7 (° F) | 304 | 303 | 297 | 287 |
| TF14C (° F) | 327 | 325 | 315 | 296 |
| TF14P (° F) | --- | --- | --- | --- |
| TF14M (° F) | --- | --- | --- | --- |
| TO2 (° F) | 520 | 501 | 452 | 398 |
| TH2 (° F) | 496 | 472 | 413 | 358 |
| WREC (pph) | 1,500 | 1,500 | 1,503 | 1,508 |

Recirculation Fuel Weight = 61 Pounds

For this study, fuel recirculation to the aircraft main feed tank is also necessary during the final descent. Maximum flow rates on the order of 1,600 pph are necessary during this mission phase to limit maximum system temperatures to permissible levels. Fuel overtemperature conditions also occur in the operating burner lines during this final idle-descent to sea level.

B.3 Study 3

The Mission B/Study 3 incorporates JP-7 fuel at a maximum inlet fuel temperature of 250° F. The use of JP-5/8 fuel at 350 ° F inlet fuel temperature was considered as an alternative for this study, but was not deemed feasible as Mission B requires a fuel with a higher thermal stability or a lower inlet fuel supply temperature in order to obtain the necessary fuel heat sink capacity.

Figure 72 shows the fluid system for the GE14/FLITE-2D engine. Inner and outer duct ram main burner fuel/air coolers, shown in Figure 60, are located downstream of the main engine control for cooling the main burner liner cooling air. The main burner fuel schedule is changed to provide 60 percent of the total mainburner flow to the outer duct fuel/air cooler and 40 percent to the inner duct fuel/air cooler. The fuel scheduling is accomplished by the addition of a dual flow regulating servovalve in the main burner portion of the fuel control. the fuel flow for both coolers are routed downstream from the fuel control through the fuel/air coolers and into the main burner fuel nozzles through header manifolds which are integral portions of the cooler designs. The use of JP-7 fuel simplifies the cooling requirements for the core, ram preburner and ram main burner fuel lines when these respective burners are not in operation. Where for JP-5 fuel, a temperature dependent recirculating system was necessary to meet the fuel thermal stability requirements, the use of JP-7 fuel permits a constant flow of 100 pph to be supplied to the burner lines when the respective burners are not in operation. This flow is of such a negligible quantity that it is considered expendable.

A summary of the GE14/FLITE-2D engine weight changes for the four lubricant/hydraulic fluids is given in Table LVII.

Figures 73 to 76 depict the engine fluid temperature profiles for JP-7 fuel and the candidate fluids used in the lubrication and fluid power systems. The use of the ramburner liner cooling air fuel/air heat exchangers causes maximum fuel system temperatures of approximately 1000° F during the cruise-out portion of the mission. These temperatures occur in the fuel/air heat exchangers and permit a reduction of from 30% $W_{25}$ to 15.5% $W_{25}$ in the quantity of cooling air required for the main burner liner. Location of the fuel/air coolers adjacent to the main burner permits a short residence time at elevated temperatures and minimizes the potential for blockage of the fuel lines due to thermal degradation products.

The idle-descent recirculation fuel summaries are given in Tables LVIII to LXI. Recirculation of fuel to the aircraft main feed tank is necessary during the ramjet idle-descent to restrict the operating temperatures of the fluid power and lubrication systems to within the prescribed bulk oil stability limits.

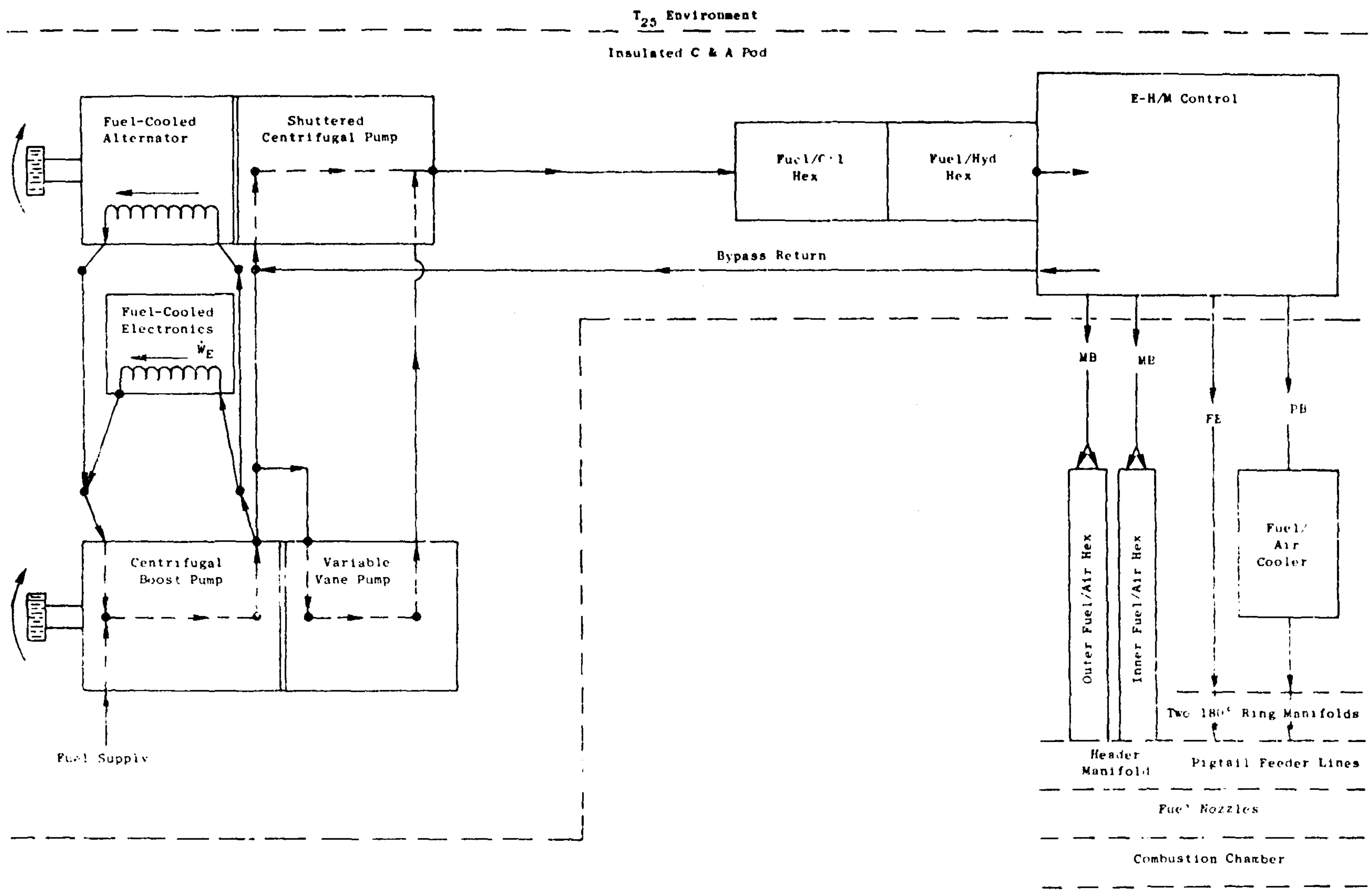



Figure 72. Mission B/Study 3 Fluid System Schematic.

Table LVII. GE14/FLITE-2D Engine Weight Changes for the Candidate Lubricants.

| | MIL-L 27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|
| | | 201.5% Engine | | |
| Fuel System | 129.2 lb | 129.2 lb | 129.2 lb | 129.2 lb |
| Fluid Power | 0 | 16.7 | 19.3 | 159.7 |
| Lubrication System | 0 | -2.7 | -13.4 | 14.3 |
| Delta Weight | 129.2 lb | 143.2 lb | 135.1 lb | 303.2 lb |
| | | 100.0% Engine | | |
| Fuel System | 62.1 lb | 62.1 lb | 62.1 lb | 62.1 lb |
| Fluid Power | 0 | 12.1 | 13.9 | 115.4 |
| Lubrication System | 0 | -1.5 | -9.2 | 10.5 |
| Delta Weight | 62.1 lb | 72.7 lb | 66.8 lb | 188.0 lb |

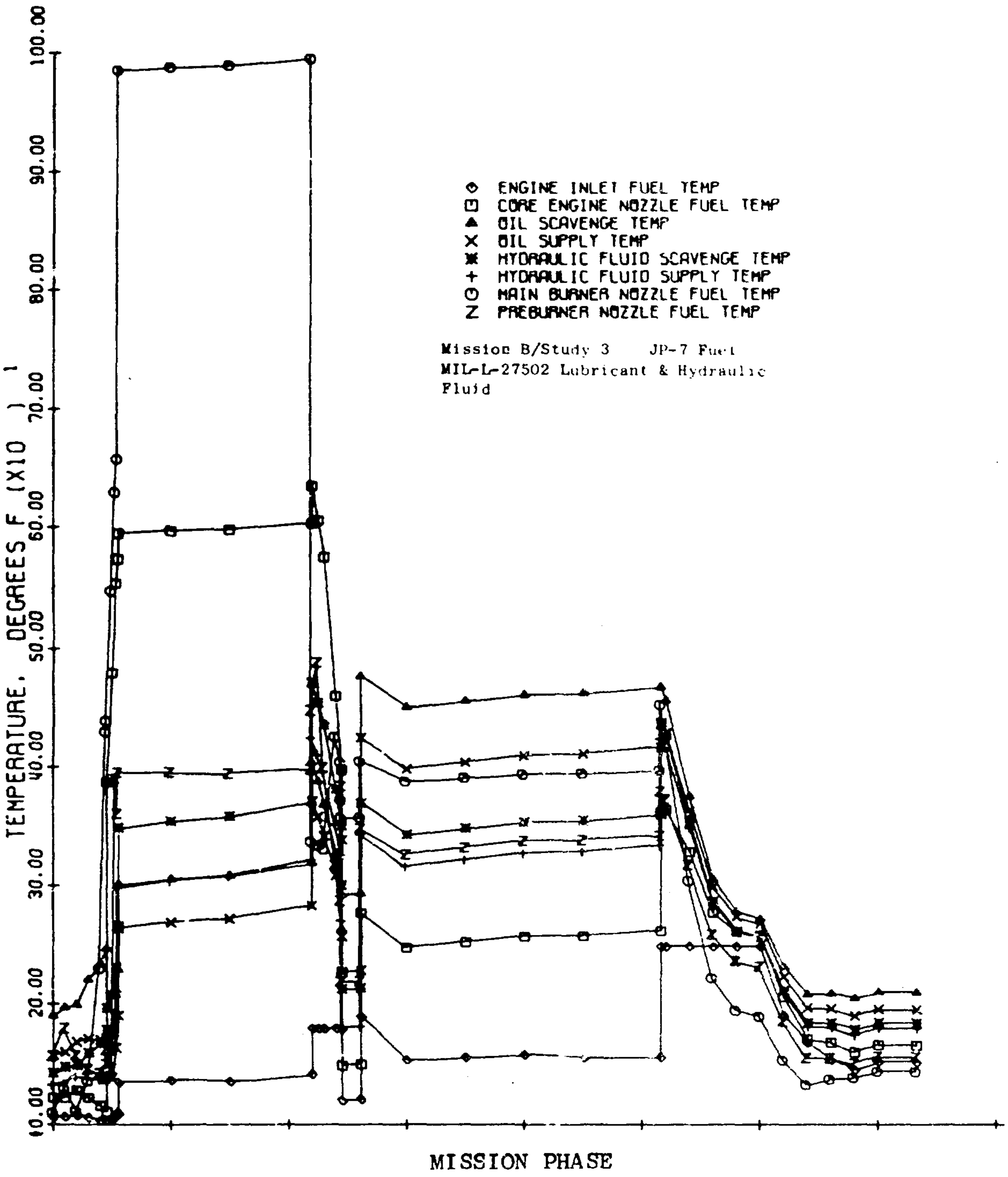



Figure 73. GE14/FLITE-2D Thermal Profiles, MIL-L-27502.

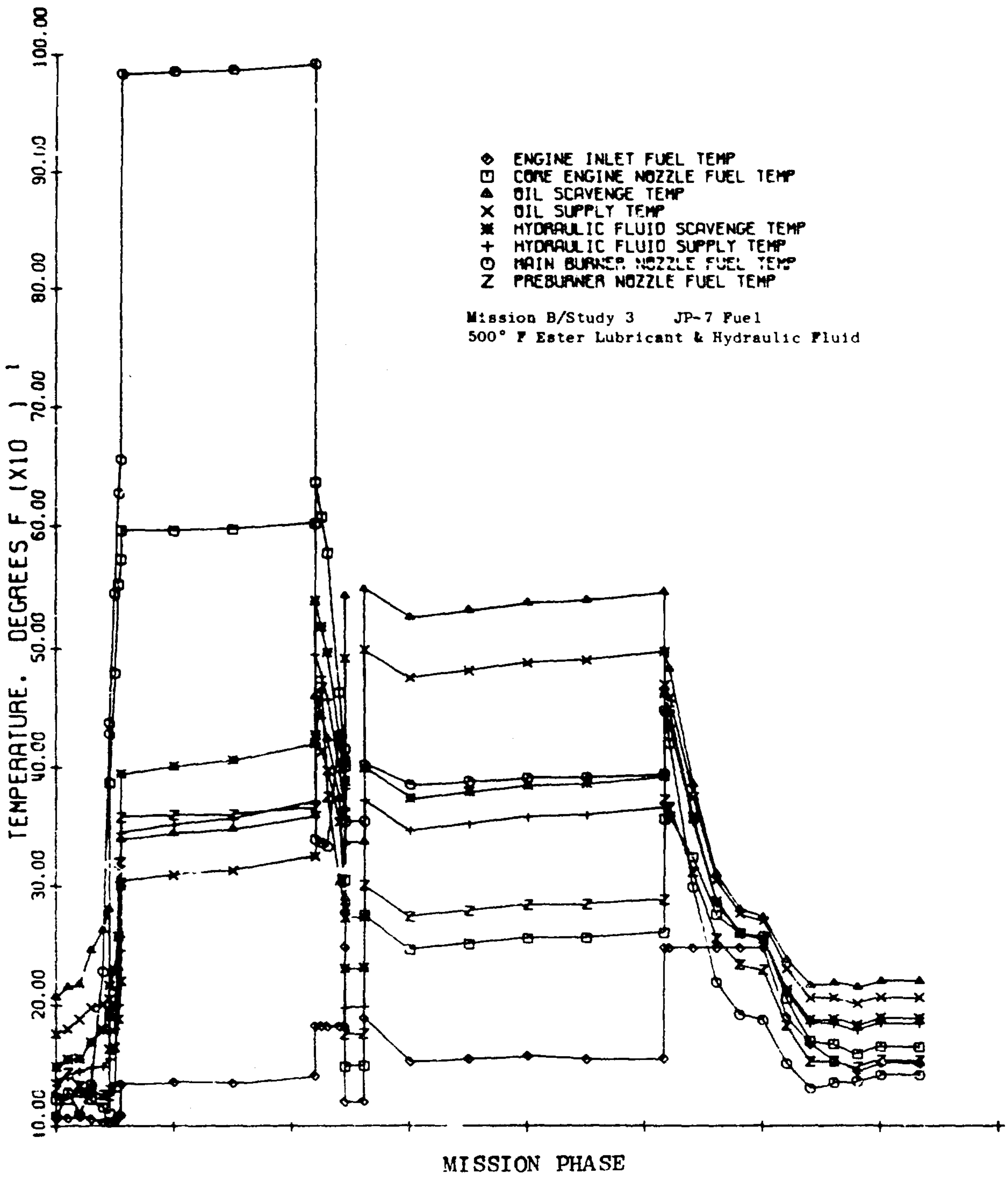



Figure 74. GE14/FLITE-2D Thermal Profiles, 500° F Ester.

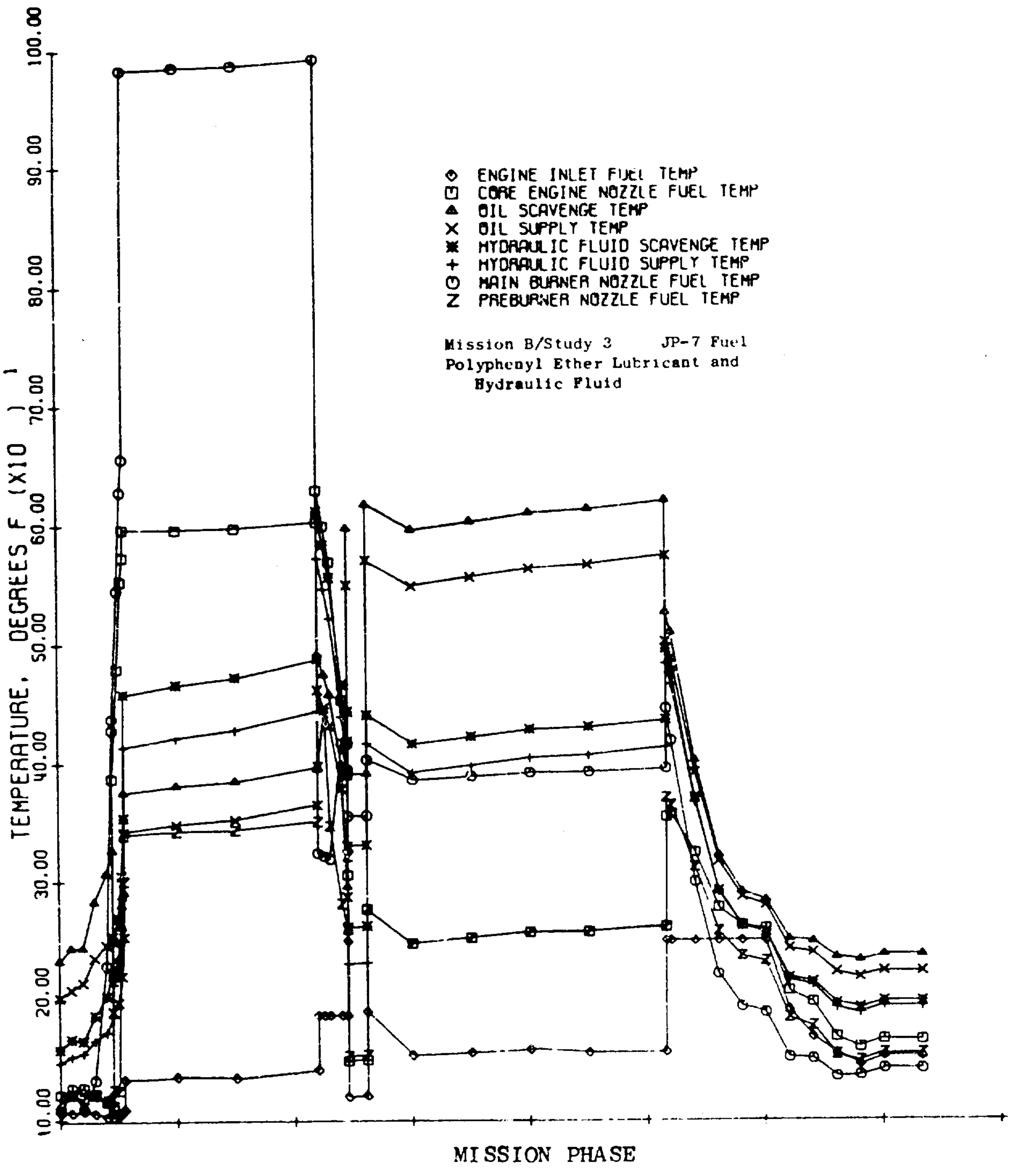



Figure 75. GE14/FLITE-2D Thermal Profiles, Polyphenyl Ether.

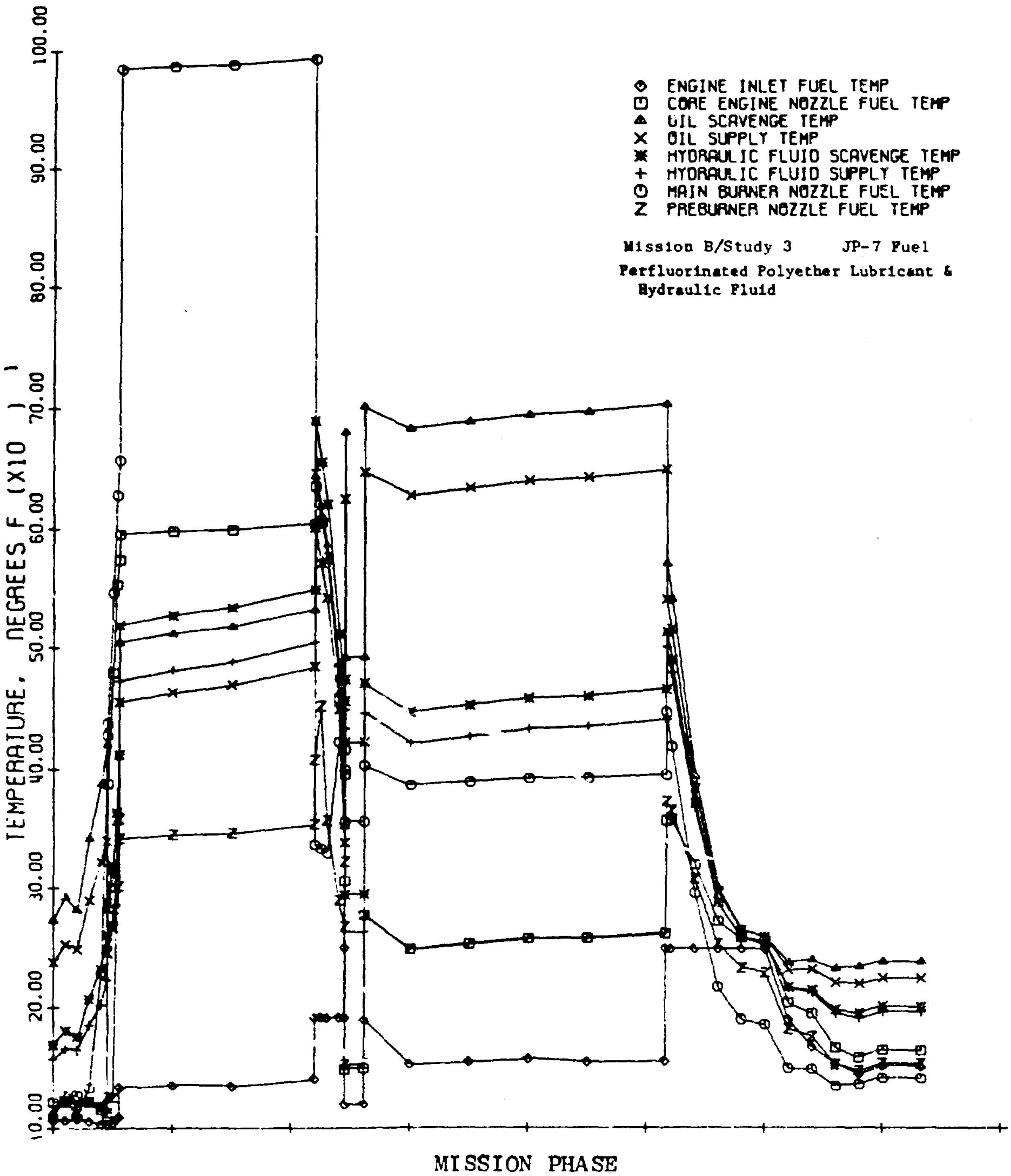



Figure 76. GE14/FLITE-2D Thermal Profiles, Perfluorinated Polyether.

Table LVIII. GE14/FLITE-2D Ramjet Idle-Descent Summary, MIL-L-27502.

201.5% Engine

| Time Minutes | 0.00 | 0.52 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|---|
| TFO (° F) | 180 | 180 | 180 | 180 | 180 | 180 |
| TF7 (° F) | 274 | 271 | 266 | 257 | 248 | 219 |
| TF14C (° F) | 637 | 607 | 577 | 462 | 399 | 229 |
| TF14P (° F) | 448 | 488 | 400 | 317 | 287 | 384 |
| TF14EM (° F) | 324 | 322 | 320 | 421 | 422 | 392 |
| TF14IM (° F) | 348 | 347 | 345 | 494 | 496 | 465 |
| WREC (pph) | 9,000 | 9,011 | 9,026 | 9,054 | 9,085 | 9,124 |

Recirculation Fuel Weight = 381 pounds

Table LIX. GE14/FLITE-2D Ramjet Idle-Descent Summary, 500° F Ester.

201.5% Engine

| Time Minutes | 0.00 | 0.52 | 1.02 | 2.02 | 2.51 |
|---|---|---|---|---|---|
| TFO (° F) | 183 | 183 | 183 | 183 | 183 |
| TF7 (° F) | 279 | 276 | 272 | 264 | 253 |
| TF14C (° F) | 639 | 610 | 580 | 465 | 403 |
| TF14P (° F) | 426 | 429 | 377 | 307 | 283 |
| TF14EM (° F) | 329 | 327 | 325 | 425 | 425 |
| TF14IM (° F) | 353 | 352 | 350 | 498 | 499 |
| WREC (pph) | 8,500 | 8,510 | 8,522 | 8,548 | 8,579 |

Recirculation Fuel Weight = 359 Pounds

Table LX. GE14/FLITE-2D Ramjet Idle-Descent Summary, Polyphenyl Ether.

201.5% Engine

| Time Minutes | 0.00 | 0.52 | 1.02 | 2.02 | 2.51 |
|---|---|---|---|---|---|
| TF0 (° F) | 187 | 187 | 187 | 187 | 187 |
| TF7 (° F) | 263 | 260 | 257 | 247 | 236 |
| TF14C (° F) | 630 | 601 | 571 | 455 | 392 |
| TF14P (° F) | 398 | 445 | 348 | 282 | 261 |
| TF14EM (° F) | 313 | 311 | 309 | 413 | 414 |
| TF14IM (° F) | 337 | 336 | 335 | 488 | 490 |
| WREC (pph) | 8,000 | 8,009 | 8,018 | 8,044 | 8,073 |

Recirculation Fuel Weight = 337 pounds

Table LXI. GE14/FLITE-2D Ramjet Idle-Descent Summary, Perfluorinated Polyether.

201.5% Engine

| Time Minutes | 0.00 | 0.52 | 1.02 | 2.02 | 2.51 |
|---|---|---|---|---|---|
| TF0 (° F) | 192 | 192 | 192 | 192 | 192 |
| TF7 (° F) | 277 | 273 | 268 | 257 | 245 |
| TF14C (° F) | 637 | 606 | 577 | 460 | 397 |
| TF14P (° F) | 409 | 454 | 358 | 291 | 269 |
| TF14EM (° F) | 325 | 323 | 320 | 420 | 419 |
| TF14IM (° F) | 349 | 347 | 346 | 493 | 494 |
| WREC (pph) | 7,500 | 7,503 | 7,514 | 7,535 | 7,565 |

Recirculation Fuel Weight = 316 pounds

Balancing of the airframe heat load with the quantities of recirculation fuel flows necessary for each fluid produced the inlet fuel temperature/recirculation flow combinations shown in the tables. Recirculation is not required during the final descent to sea level.

### B.4 Study 4

Mission B/Study 4 allows the maximum JP-7 engine interface fuel temperature to increase to 350° F. The fluid system for the GE14/FLITE-2E engine is shown in Figure 77. The lubrication and fluid power systems are the same as those defined for Mission B/Study 3 (JP-7 at 250° F).

Some changes were necessary in the fuel delivery system due to the increase in interface fuel temperature. These changes included the following:

- The material in the main engine control was changed from aluminum to titanium.
- A gearbox driven refrigeration unit was required in the electronic flow cooling loop to insure cooling and safe operation of the electronic control.
- The elevated fuel inlet temperature required further conversion of fuel system piping from titanium to stainless steel.
- Although the size of the ramburner liner cooling air fuel/air cooler remained the same, the quantity of liner cooling air was increased from 15.5% $W_{25}$ to 16.5% $W_{25}$.

The weight changes for the GE14/FLITE-2E fuel delivery system are listed in Table LXIII. The fluid power and lubrication system weights did not change. A summary of the incremental weight changes for the Study 4 engine is given in Table LXII.

The thermal profiles for each of the four lubricants are shown in Figures 78 to 81 and the recirculation summaries are listed in Tables LXIV to LXVII. For the final descent to sea level, fuel recirculation is needed for the MIL-L-27502 and 500° F ester fluids. This reaches a maximum of 8,500 pph for the MIL-L-27502 lubricant. As with all the previous studies, recirculation is necessary during the ramjet idle descent mission phase for all four fluids to maintain them within their bulk oil stability limits.

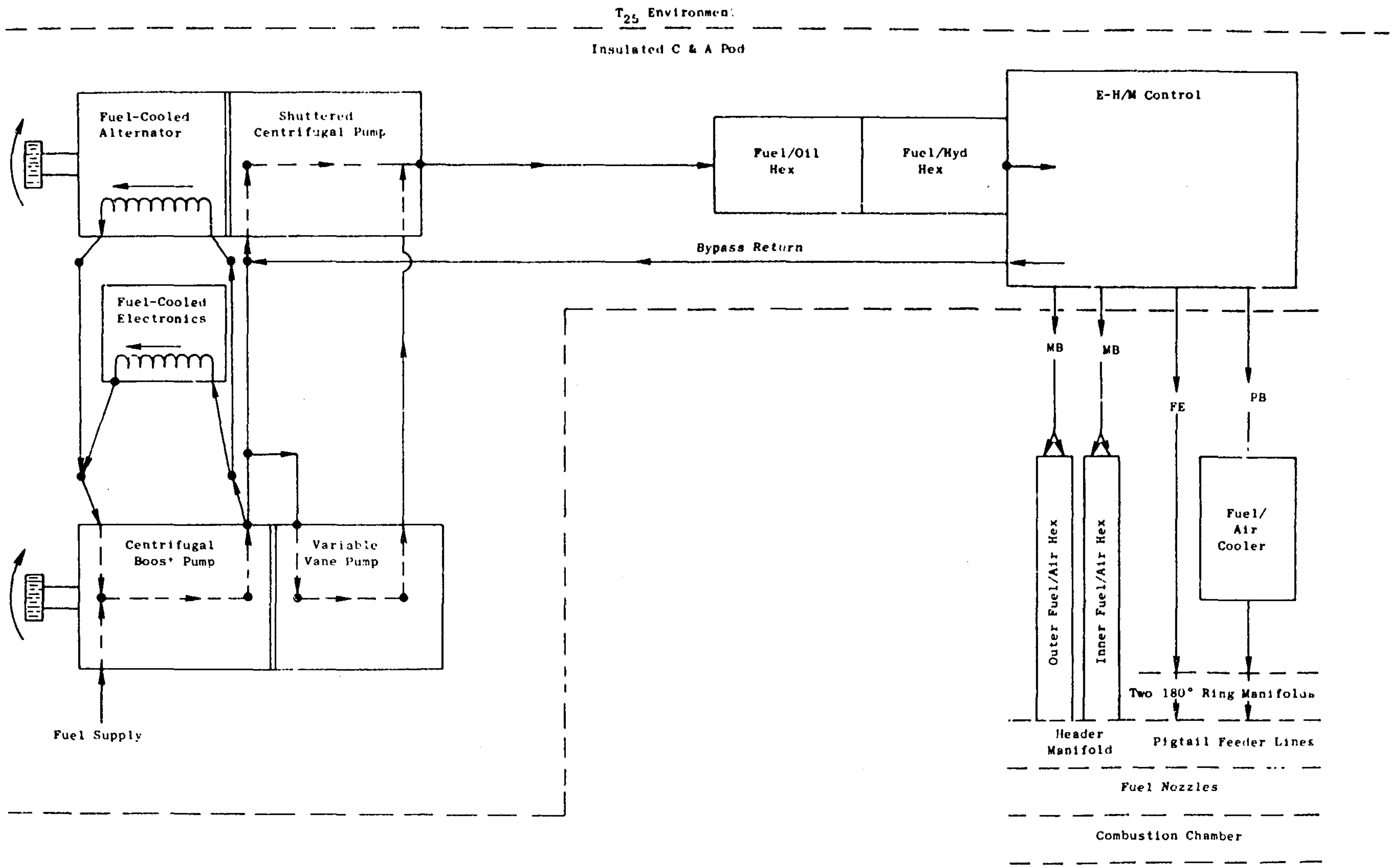



Figure 77. Mission B/Study 4 Fluid System Schematic.

Table LXII. GE14/FLITE-2E Fuel Delivery System Weight Comparison.

| Fuel System[1] Components | GE14/FLITE-2A (Baseline) (JP-5 @ 200° F) | GE14/FLITE-2E (JP-7 @ 350° F) |
|---|---|---|
| Refrigerator | 0 lb | 8.3 lb |
| Main Engine Control | 37 | 47.8 |
| Inner/Outer MB Duct H-X. | 0 | 138.1 |
| MB Fuel Lines & Insul. | 13.5 | 2.1 |
| MB Manifold Fuel Recirculating Sys. | 1.3 | 0.0 |

1 Only components that change weight are listed.

Table LXIII. GE14/FLITE-2E Engine Weight Changes for the Candidate Lubricants.

| | MIL-L-27502 | 500° F Ester | Polyphenyl Ether | Perfluorinated Polyether |
|---|---|---|---|---|
| | | 201.5% Engine | | |
| Fuel System | 144.5 lb | 144.5 lb | 144.5 lb | 144.5 lb |
| Fluid Power | 0 | 16.7 | 19.3 | 159.7 |
| Lubrication System | 0 | -2.7 | -13.4 | 14.30 |
| Delta Weight = | 144.5 lb | 158.5 lb | 150.4 lb | 318.5 lb |
| | | 100% Engine | | |
| Fuel System | 73.1 lb | 73.1 lb | 73.1 lb | 73.1 lb |
| Fluid Power | 0 | 12.1 | 13.9 | 115.4 |
| Lubrication System | 0 | -1.5 | -9.2 | 10.5 |
| Delta Weight = | 73.1 lb | 83.7 lb | 77.8 lb | 199.0 lb |

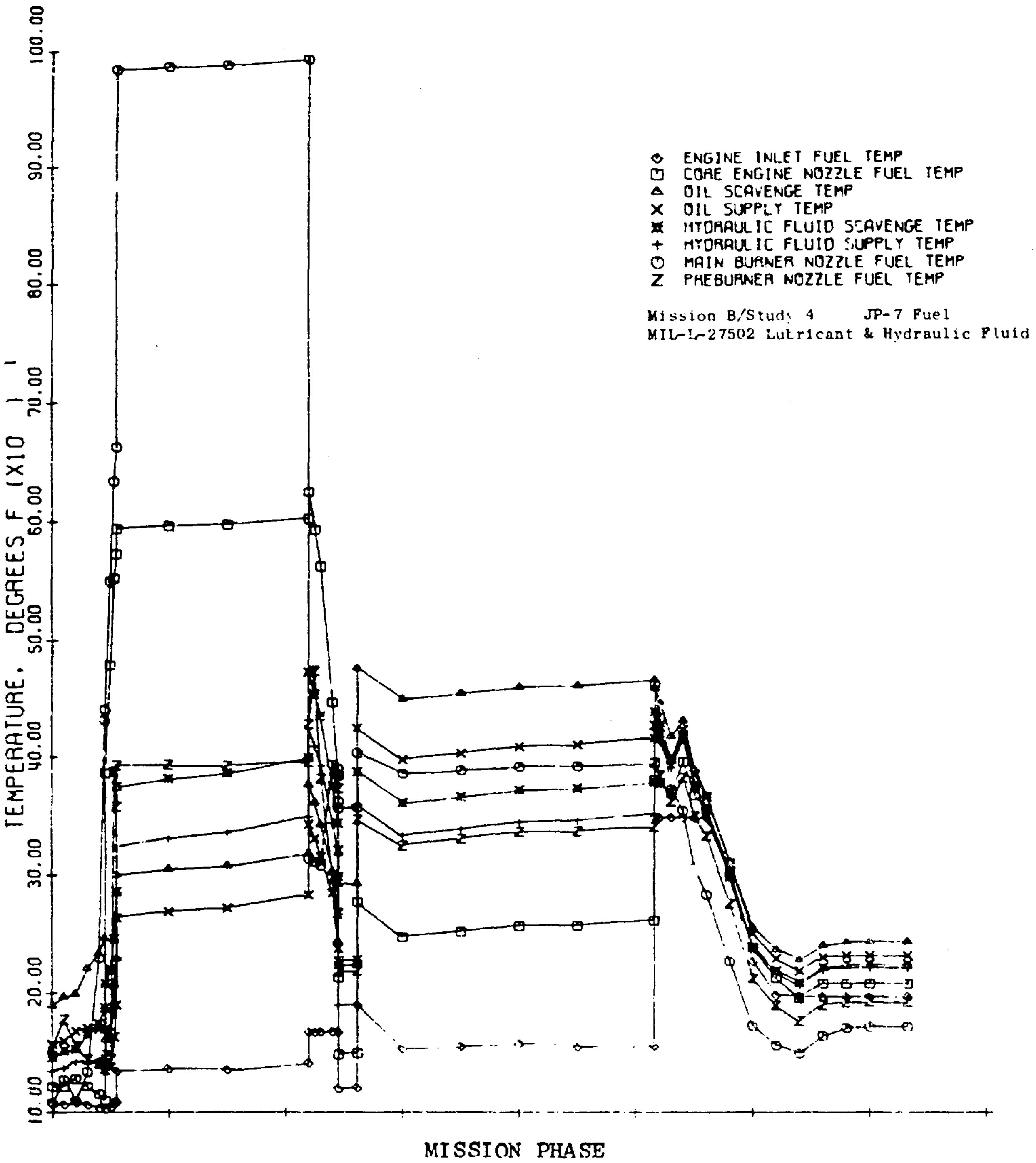



Figure 78. GE14/FLITE-2E Thermal Profiles, MIL-L-27502.

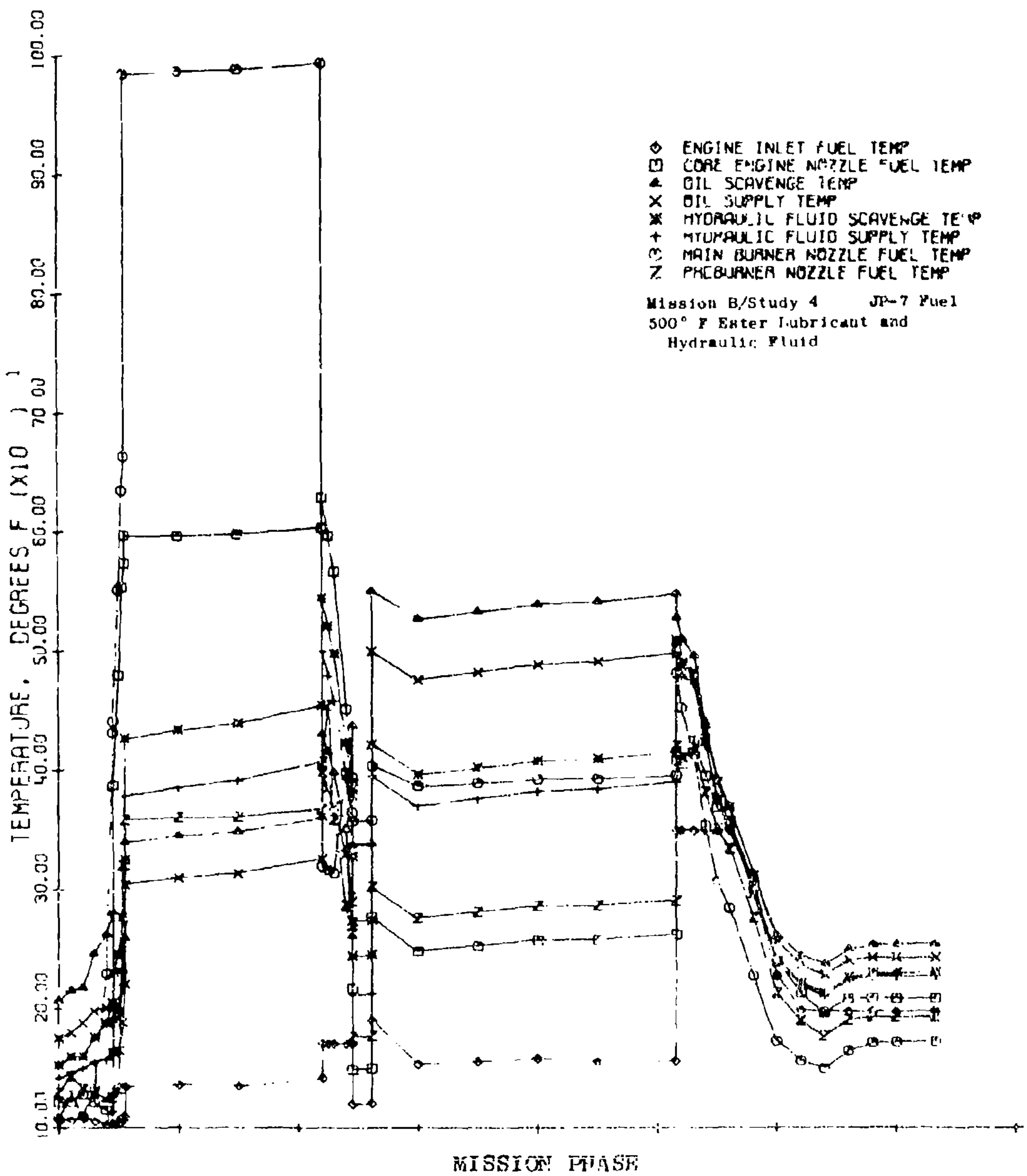



Figure 79. GE14/FLITE-2E Thermal Profiles, 500° F Ester.

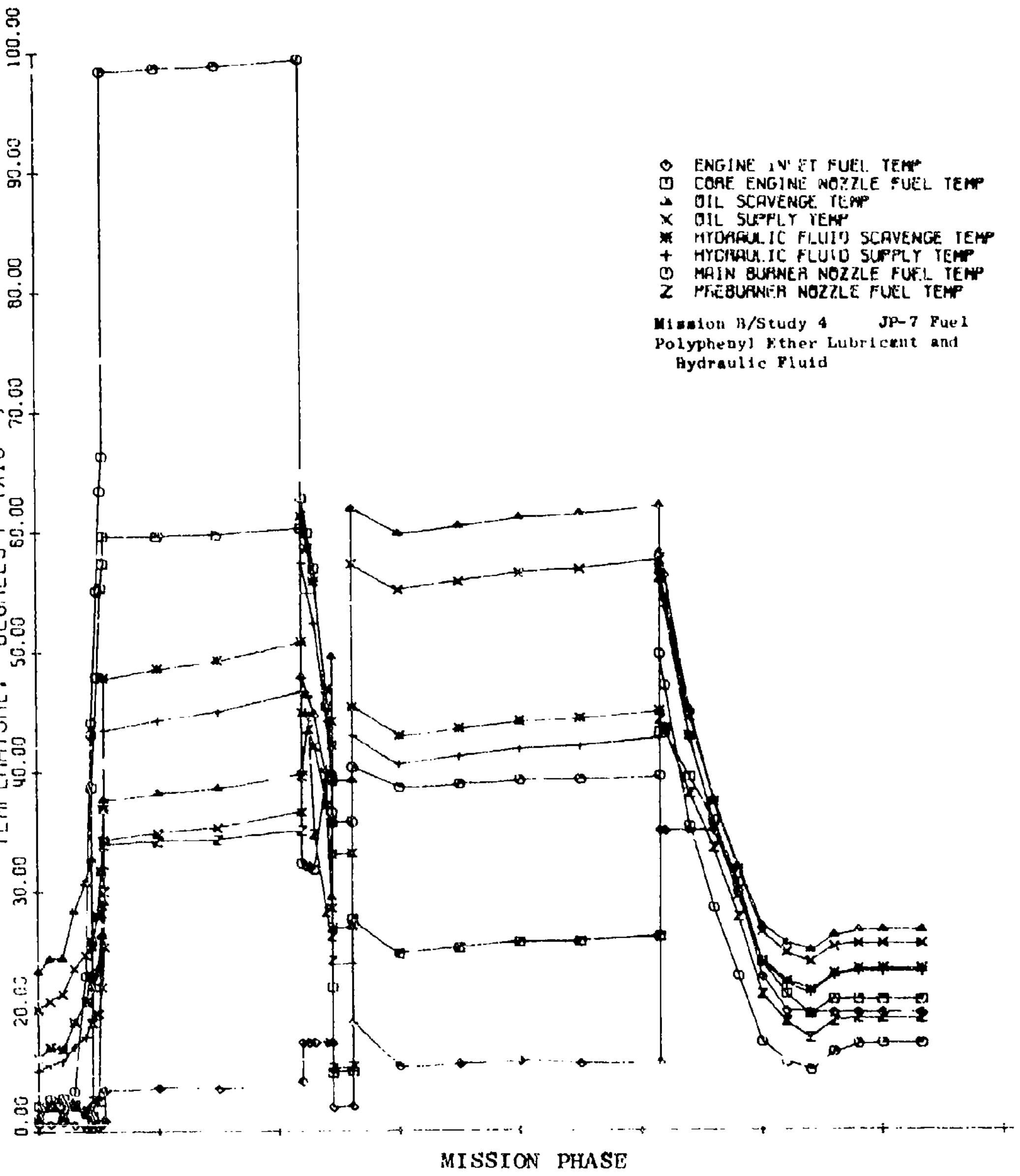



Figure 80. GE14/FLITE-2F Thermal Profiles, Polyphenyl Ether.

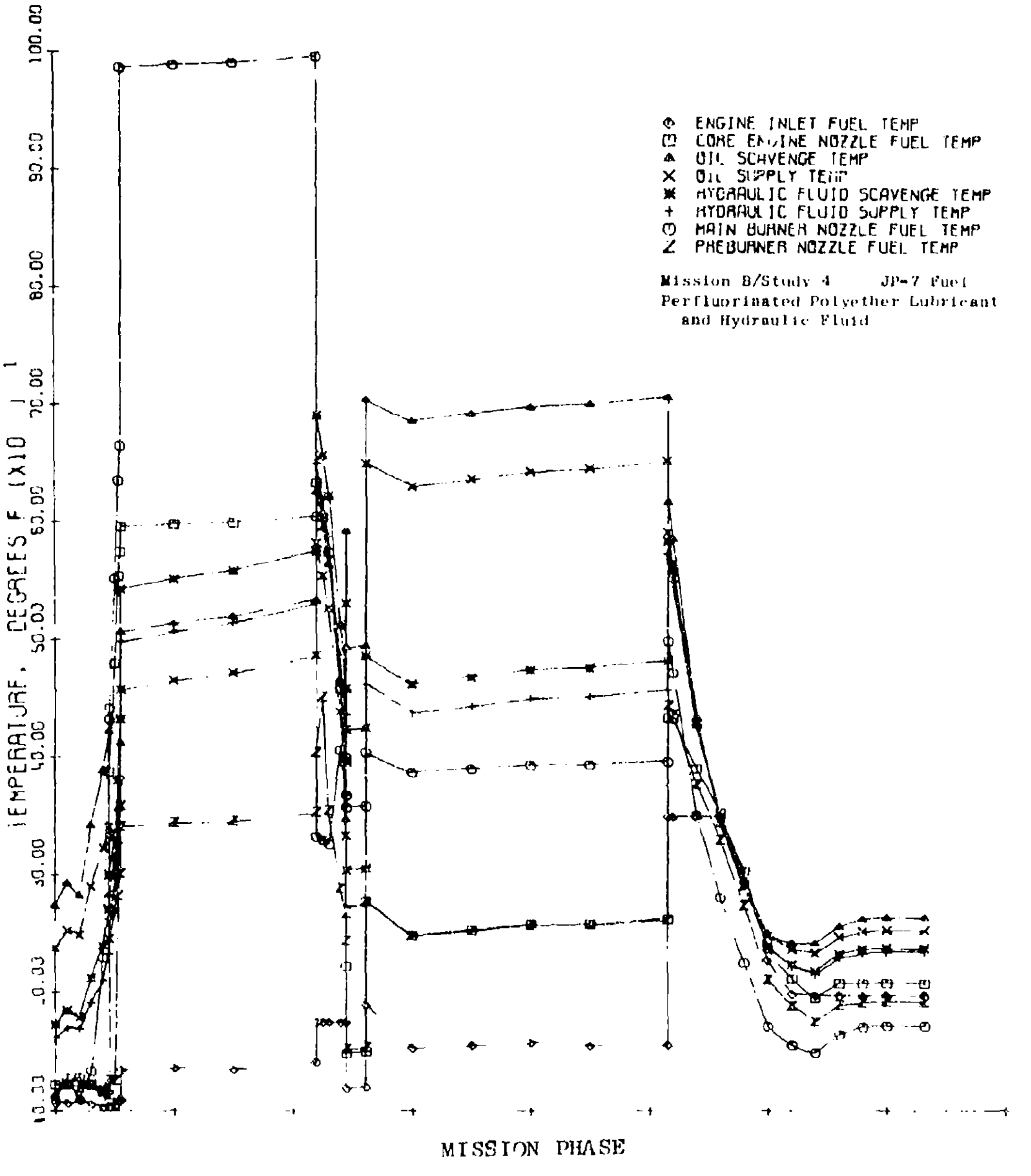



Figure 81. GE14/FLITE-2E Thermal Profiles, Perfluorinated Polyether.

Table LXIV. GE14/FLITE-2E Idle-Descent Summary, MIL-L-27502.

(a) Ramjet Idle-Descent

201.5% Engine

| Time Minutes | 0.00 | 0.52 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|---|
| TFO (° F) | 168 | 168 | 168 | 168 | 168 | 168 |
| TF7 (° F) | 251 | 248 | 244 | 236 | 227 | 205 |
| TF14C (° F) | 627 | 596 | 565 | 449 | 387 | 215 |
| TF14P (° F) | 430 | 476 | 384 | 299 | 269 | 376 |
| TF14EM (° F) | 303 | 301 | 299 | 390 | 410 | 385 |
| TF14IM (° F) | 328 | 327 | 325 | 459 | 487 | 460 |
| WREC (° F) | 11,000 | 11,012 | 11,026 | 11,055 | 11,087 | 11,109 |

ecirculation Fuel Weight = 465 Pounds

(b) Idle-Descent to Sea Level

| Time Minutes | 0.00 | 0.43 | 1.43 | 2.43 |
|---|---|---|---|---|
| TFO (° F) | 350 | 350 | 350 | 350 |
| TF7 (° F) | 367 | 366 | 361 | 399 |
| TF14C (° F) | 383 | 381 | 372 | 399 |
| TF14P (° F) | 398 | 387 | 365 | 385 |
| TF14EM (° F) | 442 | 418 | 367 | 357 |
| TF14IM (° F) | 482 | 447 | 375 | 346 |
| WREC (pph) | 8,500 | 8,506 | 8,521 | 0 |

Recirculation Fuel Weight = 345 Pounds

Table LXV. GE14/FLITE-2E Idle-Descent Summary, 500° F Ester.

(a) Ramjet Idle-Descent

201.5% Engine

| Time Minutes | 0.00 | 0.52 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|---|
| TFO (° F) | 171 | 171 | 171 | 171 | 171 | 171 |
| TF7 (° F) | 256 | 253 | 250 | 242 | 233 | 208 |
| TF14C (° F) | 630 | 598 | 568 | 453 | 391 | 218 |
| TF14P (° F) | 408 | 456 | 360 | 288 | 264 | 291 |
| TF14EM (° F) | 307 | 306 | 304 | 394 | 413 | 386 |
| TF14IM (° F) | 332 | 331 | 330 | 463 | 490 | 461 |
| WREC (pph) | 10,500 | 10,510 | 10,522 | 10,550 | 10,582 | 10,612 |

Recirculation Fuel Weight = 444 Pounds

(b) Idle-Descent to Sea Level

| Time Minutes | 0.00 | 0.43 | 1.43 |
|---|---|---|---|
| TFO (° F) | 350 | 350 | 350 |
| TF7 (° F) | 393 | 391 | 419 |
| TF14C (° F) | 410 | 407 | 426 |
| TF14P (° F) | 422 | 411 | 418 |
| TF14EM (° F) | 462 | 437 | 410 |
| TF14IM (° F) | 498 | 463 | 412 |
| WREC (pph) | 1,600 | 1,601 | 0 |

Recirculation Fuel Weight = 38 Pounds

Table LXVI. GE14/FLITE-2E Ramjet Idle-Descent Summary,
Polyphenyl Ether.

201.5% Engine

| Time Minutes | 0.00 | 0.52 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|---|
| TFO (° F) | 174 | 174 | 174 | 174 | 174 | 174 |
| TF7 (° F) | 261 | 258 | 255 | 247 | 238 | 211 |
| TF14C (° F) | 630 | 601 | 571 | 456 | 394 | 221 |
| TF14P (° F) | 398 | 447 | 349 | 284 | 263 | 243 |
| TF14EM (° F) | 312 | 310 | 309 | 397 | 417 | 388 |
| TF14IM (° F) | 336 | 335 | 335 | 466 | 492 | 463 |
| WREC (pph) | 10,000 | 10,010 | 10,020 | 10,046 | 10,078 | 10,014 |

Recirculation Fuel Weight = 422 Pounds

Table LXVII. GE14/FLITE-2E Ramjet Idle-Descent Summary,
Perfluorinated Polyether.

201.5% Engine

| Time Minutes | 0.00 | 0.52 | 1.02 | 2.02 | 2.51 | 2.52 |
|---|---|---|---|---|---|---|
| TFO (° F) | 176 | 176 | 176 | 176 | 176 | 176 |
| TF7 (° F) | 271 | 268 | 264 | 254 | 244 | 214 |
| TF14C (° F) | 635 | 605 | 576 | 460 | 398 | 225 |
| TF14P (° F) | 406 | 453 | 356 | 290 | 269 | 246 |
| TF14EM (° F) | 321 | 319 | 317 | 403 | 420 | 390 |
| TF14IM (° F) | 345 | 344 | 342 | 470 | 495 | 464 |
| WREC (pph) | 9,500 | 9,511 | 9,524 | 9,555 | 9,588 | 9,633 |

Recirculation Fuel Weight = 402 Pounds

## C. Interceptor Design & Performance

The Mission B interceptor evaluation included the effects of fuel thermal limits on both aircraft and engine systems for the matrix of four engine lubricants. A summary of the study aircraft is presented in Table LXVIII. Study 1 and Study 2 provide a measure of the impact on aircraft and engine performance of the maximum allowable engine/airframe fuel interface temperature for a JP-5/6 class fuel at 150° F and 250° F. Study 3 and Study 4 provide a similar comparison for a JP-7 class fuel at 250° F and 350° F. Additionally, the results of Study 2 and Study 3 illustrate the influence of fuel thermal stability on engine and resulting interceptor performance. The combined result of the fuel change and interface fuel temperature increase from the heaviest interceptor (Study 1) to the lightest interceptor (Study 4) was a 3,300 lb. reduction in TOGW.

The influence of lubricant selection on engine weight and resulting interceptor performance was of second order as compared to fuel effects with the exception of perfluorinated polyether. The minor weight variations discussed in subsequent sections cannot be considered sufficient to permit specific lubricant selection recommendations solely on a bulk oil temperature capability basis.

### C.1 Interceptor Design

The range of size for the Mission B interceptors designs are illustrated in Figure 82. These configurations are sized for the Mach 4+ mission. The major performance characteristics are presented in Table LXIX for the four designs. The aircraft design inputs and sizing criteria are identical for all of these interceptors as presented in Section III.

As the interface temperature is increased, both the interceptor size and weight are reduced, primarily due to improved engine performance. Additional interceptor weight variations are obtained due to changes in airframe subsystem and engine weights. The rationale behind the performance and weight variations are presented in subsequent paragraphs.

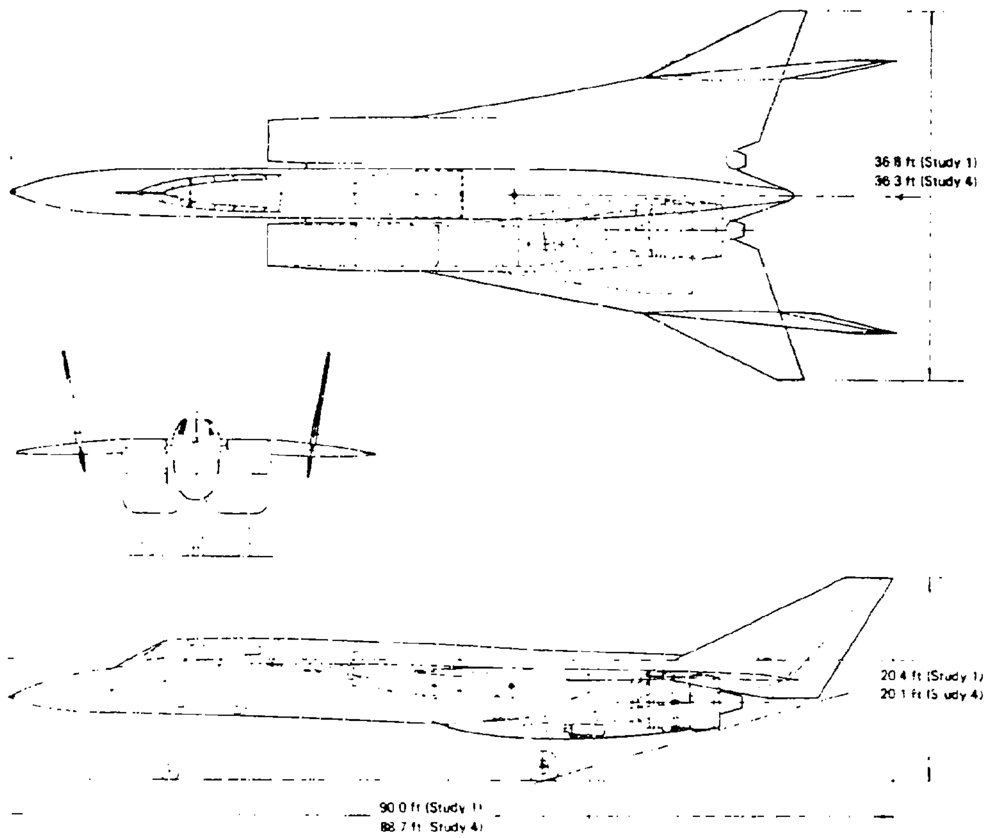
### C.2 Mission Performance

The GE14/FLITE-2A propulsion system described in Section III was modified to reflect changes in fuel, lubricant, and engine/airframe fuel interface temperature for the four Mission B studies. The increasing engine weight with increasing interface temperature is due in part to changes in the fluid power and lubrication systems to accommodate this higher fuel temperature. Within the range of engine/airframe fuel temperatures investigated, the engine performance improved with increasing temperatures. An approximate 0.2% increase in thrust and 0.3% reduction in SFC are obtained over the entire flight profile for each 100° F increase in interface temperature. These improvements result from improved engine cycle thermal efficiency due to the increasing fuel interface temperature. It is anticipated that further improvements in engine performance with increasing interface temperature may be limited by either material limitations and/or fluid system design and operational complexity.

Table LXVIII. Mission B Summary.

| | Study 1 | Study 2 | Study 3 | Study 4 |
|---|---|---|---|---|
| Engine GE14/FLITE | 2B | 2C | 2D | 2E |
| Fuel | JP-5/8 | JP-5/8 | JP-7 | JP-7 |
| Engine/Airframe Interface Temp. (° F) | 150 | 250 | 250 | 350 |
| Fuel Loading Temp. | Amb. | Amb. | Amb. | Amb. |
| Fuel Density @ Loading Temperature (psf) | 51.8 | 51.8 | 51.8 | 51.8 |
| ECS Type | Vapor Cycle | Vapor Cycle | Vapor Cycle | Vapor Cycle |
| ECS Weight (lb) | 734 | 672 | 672 | 669 |

All engines use polyphenyl ether lubricant.




| Propulsion |
|---|
| (2) GE14 FLITE Turboramjet Engines |

| Armament and Fire Control |
|---|
| 4 Long Range Air to Air Missiles at 500 lb Each |
| 48 in. Dish Phased Array, Radar |

| Physical Characteristics | | | |
|---|---|---|---|
| | Wing | Wing Tip | Vert Tail |
| Aspect Ratio | 0.529 | 1.56 | 0.920 |
| Taper Ratio | 0.191 | 0.175 | 0.279 |
| Dihedral | −3° | -3° | |
| Airfoil Section | NACA64A003 | NACA64A003 | NACA64A003 |
| Airfoil Thickness | 3% | 3% | 3% |
| Leading Edge Sweep | 79.7° | 65° | 65° |
| Trailing Edge Sweep | 20° | 20° | 27.5° |

Figure 82. Mission B Interceptor.

Table LXIX. Mission B Major Performance Characteristics.

| | Study 1 | Study 2 | Study 3 | Study 4 |
|---|---|---|---|---|
| Take-off Gross Weight (lb) | 89,000 | 87,000 | 86,000 | 85,700 |
| Wing Area ($ft^2$) (Including Tips) | 1,160 | 1,140 | 1,130 | 1,120 |
| Engine/Airframe Fuel Interface Temperature (° F) | 150 | 250 | 250 | 350 |
| Fuel Type | JP-5/8 | JP-5/8 | JP-7 | JP-7 |

Additional engine performance increments are obtained for the -2D and -2E engines by using the higher heat sink of JP-7 to precool the ramburner liner cooling air. By lowering the air temperature, the quantity of ramburner liner cooling air is reduced by approximately 50%. This decrease in secondary air produces significant improvements in engine thrust and SFC. The increase in weight for the JP-7 fueled engines results from the incorporation of fuel/air heat exchangers to cool the ramburner liner cooling air.

### C.3 Alternate Lubricants

The influence of lubricant selection on engine weight for the GE14/FLITE engines is presented in Table LXX. Although MIL-L-27502 provides the lightest resultant engine for all study engines, it was not selected for use in performing the interceptors. This decision was based on an analysis which indicated that greatly increased lubricant system servicing would be required if MIL-L-27502 were used as compared to polyphenyl ether. Polyphenyl ether was, therefore selected as the most promising lubricant for all the configurations. The increase in engine weights incurred with perfluorinated polyether resulted from changes in the fluid power and lube systems primarily to accommodate the low bulk modulus and high vapor pressure of perfluorinated polyether.

The variations in aircraft TOGW to account for the changes in engine weight arising from the use of the alternate lubricants is presented in Table LXXI. The use of the alternate lubricants impose only minor weight penalties with the exception of perfluorinated polyether.

### C.4 Thermodynamic Characteristics

For each of the Mission B configurations, ECS weights and fuel temperature characteristics were determined as a function of the maximum allowable engine/airframe fuel interface temperature. Variations in ECS weight were determined by accounting for changes in the expendable subsystem requirements using the Mission B ECS concept described in Section III. The ECS weights are 734 lb for Study 1, 672 lb for Studies 2 and 3, and 669 lb for Study 4. The variation in ECS weight results from differences in the amount of expendable fuel required (to maintain acceptable refrigeration package condenser inlet fuel temperatures) and the size of the subsystem components. The fuel temperature characteristics are a function of heat added to the stored fuel via recirculation from either the airframe/engine interface or from the engines, and heat transferred to the fuel through the airframe structure. The Studies 1 through 4 aircraft considered fuel recirculation from the engines back to the airframe feed tank during the descent mission phases.

Fuel temperature profiles for the Studies 1 through 4 aircraft are presented in Figure 83. The profiles for the Studies 2 and 3 aircraft are identical due to the same 250° F interface temperature requirements.

Table LXX. Mission B Engine Weight Sensitivity.

100% Engine Size

| | MIL-L-27502 | 500° F Ester | Polyphenyl Ether | Perflaorinated Polyether |
|---|---|---|---|---|
| GE14/FLITE-2B | 2,880 lb | 2,890 lb | 2,880 lb | 3,000 lb |
| GE14/FLITE-2C | 2,880 | 2,890 | 2,880 | 3,000 |
| GE14/FLITE-2D | 2,940 | 2,950 | 2,950 | 3,070 |
| GE14/FLITE-2E | 2,950 | 2,960 | 2,960 | 3,080 |

Table LXXI. Mission B Impact of Lubricant Selection

| | MIL-L-27502 | 500° F Ester | Polyphenyl Ether | Perflaorinated Polyether |
|---|---|---|---|---|
| ΔTOGW Study 1 (lb) GE14/FLITE-2B | 0 | +100 | +50 | +700 |
| ΔTOGW Study 2 (lb) GE14/FLITE-2C | 0 | +100 | +50 | +1,250 |
| ΔTOGW Study 3 (lb) GE14/FLITE-2D | 0 | +100 | +50 | +1,250 |
| ΔTOGW Study 4 (lb) GE14/FLITE-2E | 0 | +100 | +50 | +1,250 |

ΔTOGW = TOGW MIL-L-27502 - TOGW

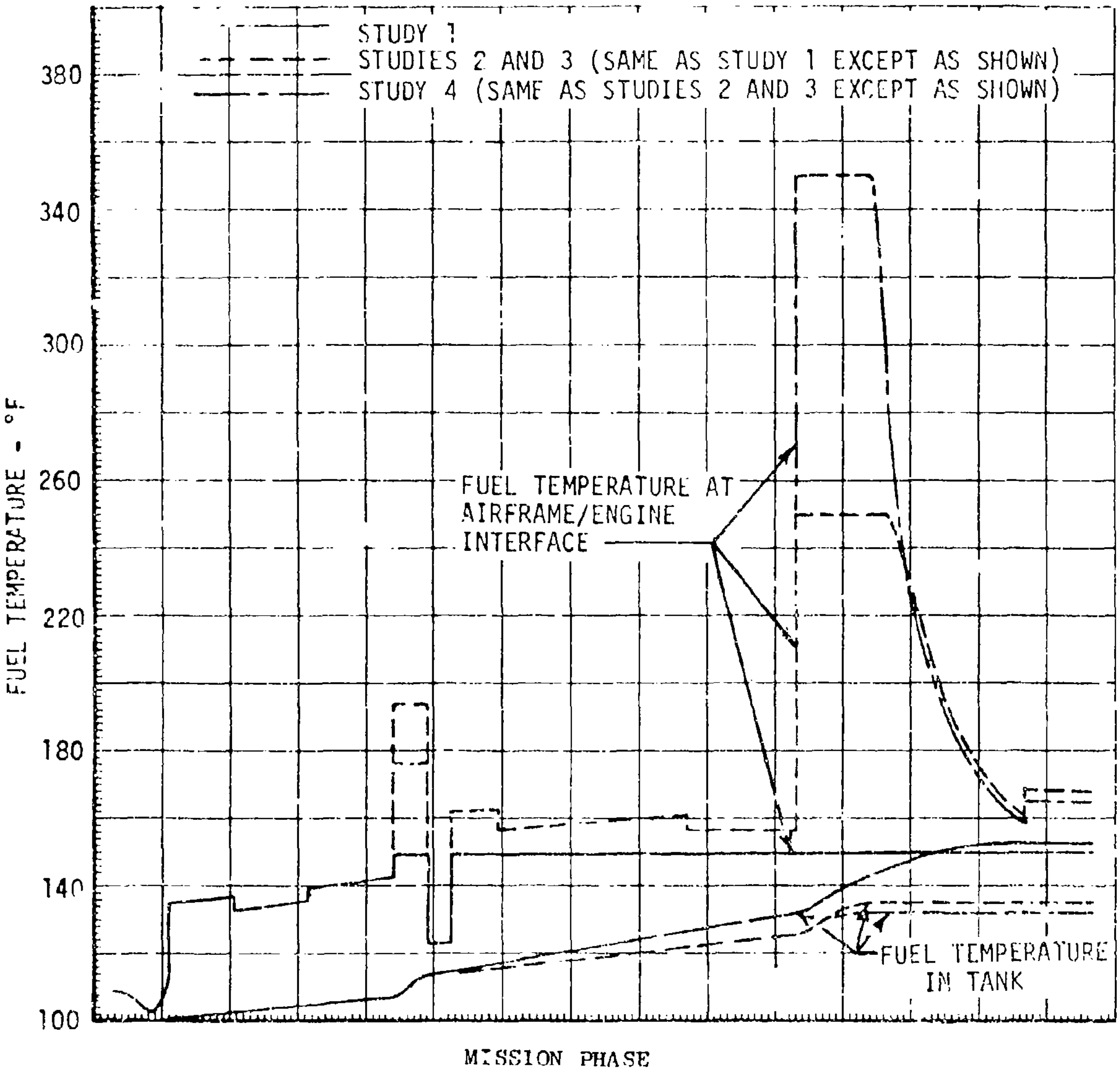



Figure 83. Fuel Temperature Profiles with Recirculation from Engines, Mission B.

## C.5 Supplemental Studies

In addition to the basic Mission B investigation two additional variations in fuel heat sink utilization were investigated, a direct fuel heat sink ECS and a cooled engine inlet duct wall configuration.

### Direct Fuel Heat Sink ECS

A direct fuel heat sink ECS concept, utilizing precooled (0° F initial temperature) fuel shows distinct advantages in minimizing TOGW. Airframe heat loads can readily be absorbed by the fuel and delivered to the engines at low interface temperatures with moderate temperature peaks during descent, as shown in Figure 84. The maximum interface temperature is experienced only during these phases of the mission and the maximum fuel temperature level is maintained by varying the quantity of fuel being recirculated to the feed tank. The precooled fuel-direct fuel heat sink ECS concept offers significant advantages over other candidate concepts in terms of reduced ECS weight and volume requirements, overall system simplicity, and increased reliability. The concept is essentially insensitive to weight and volume variations resulting from changes in allowable interface temperature.

An aircraft TOGW of ~83,000 lb for a precooled JP-7 fueled Mission B interceptor compares very favorably with other Mission B interceptor TOGW's. The system differences between the precooled fuel interceptor and the lightest Study interceptor are tabulated in Table LXXII.

Table LXXII. Precooled Fuel System Differences.

| | Precooled | Study 4 |
|---|---|---|
| ECS Weight (lb) | 460 | 668 |
| Electrical Weight (lb) | 342 | 482 |
| Fuel Temperature (° F) in A/C Tankage at Takeoff | 0 | 100 |
| Engine/Airframe Interface (Max) | 104 | 350 |

The reduction in ECS and electrical system weight are achieved through elimination of the vapor cycle compressor, electrical drive, and numerous heat exchangers. The lower engine inlet temperature permitted redesign of the engine fuel system which resulted in the lower (27 lb reduction) engine weight for each 100% engine. The lower fuel loading temperature provides an effective 2.3% increase in fuel density.

A summary of the individual effects of these differences between the precooled configuration and Study 4 are tabulated in Table LXXIII.

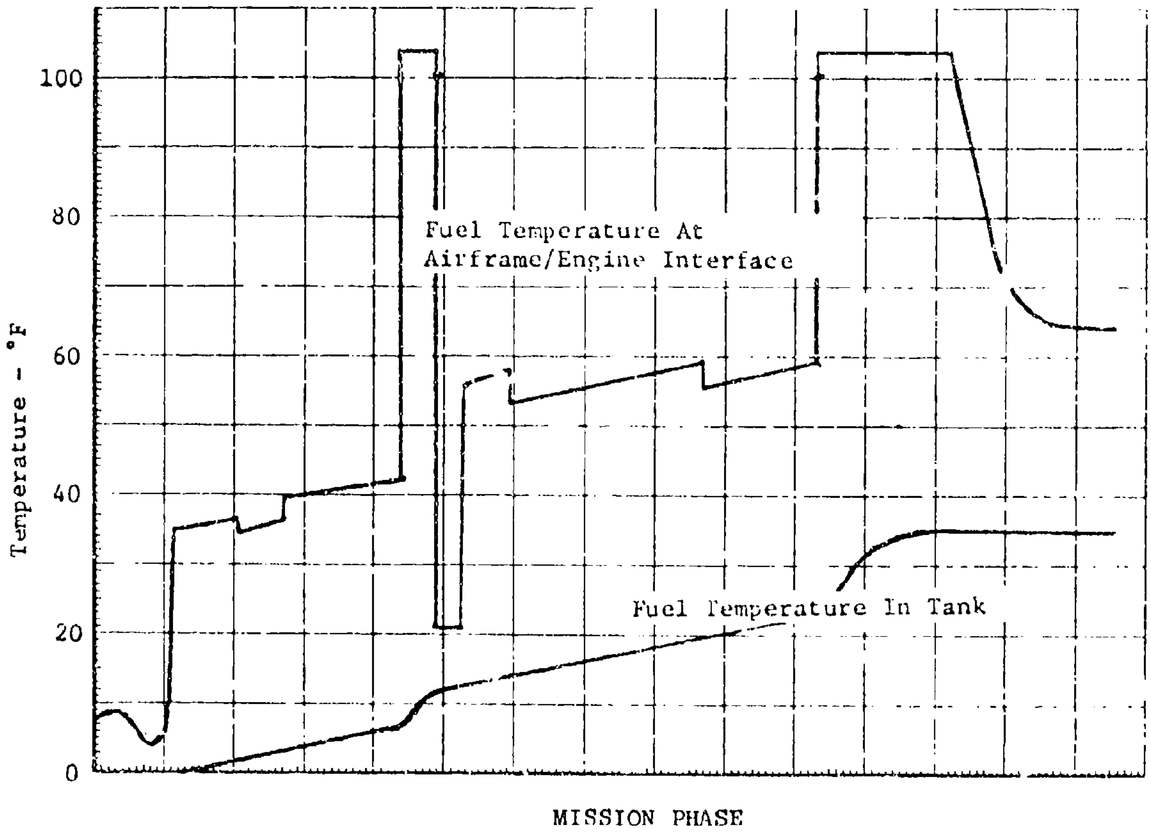



Figure 84. Fuel Temperature Profiles, Direct Fuel Heat Sink ECS.

Table LXXIII. Precooled Fuel Incremental Weight Differences.

| | |
|---|---|
| ΔTOGW Due to ECS Wt | -781 lb |
| ΔTOGW Due to Electrical Wt | -523 lb |
| ΔTOGW Due to Engine Wt | -504 lb |
| ΔTOGW Due to Fuel Density | -801 lb |
| ΔTOGW Due to Engine Performance Changes | -358 lb |
| $TOGW_{Precooled} - TOGW_{Study\ 4}$ | 2967 lb |

## Cooled Engine Inlet Duct Wall Configuration

For the Studies 2 through 4 aircraft, the maximum available heat capacity of the fuel is used only during brief mission phases where engine fuel requirements are low. For example, during the outbound cruise mission phase, fuel heat capacities in the order of 40,000 and 75,000 Btu/min are still available for the 250 and 350° F interface temperature cases, respectively, after absorbing the airframe heat loads. Since all internal heat loads are being absorbed by the fuel and the structural concept is designed to withstand the high temperature environment without active cooling, there are no unaccounted heat loads which could utilize this excess heat sink.

However, if the aircraft were to be fabricated prior to the completion of a development program for graphite nickel, conventional high temperature structural material such as René 41 would be used. This would result in a large increase in inlet weight. The inlet weight, 5,400 lb in the Mission B aircraft, would increase to over 10,000 lb by changing to René 41. A change of this magnitude would necessitate a complete resizing of the aircraft to achieve the desired acceleration and mission radius. By cooling the internal walls to a maximum temperature of approximately 800° F, titanium (rather than René 41) can be used as the structural material, resulting in a proportionate reduction in inlet weight.

An inlet heating rate distribution was determined for the Mach 4+ cruise condition, and the amount of inlet cooling that could be accomplished was determined in terms of subsonic diffuser surface area. In both the 250° F and 350° F interface temperature cases, the structural concept and heat transport loop arrangement were considered to be similar. Major differences are that the latter case permits more inlet surface area to be cooled ($172\ ft^2$ versus $105\ ft^2$) and requires larger components to be used in the heat transport loop. Temperature profiles for both cases are presented in Figure 85. When the interface temperature is at the design limit, some fuel is recirculated back to the fuel tankage at the maximum temperature. As a result, onboard fuel temperatures increase and the expendable subsystem requirements are higher than for the Studies 3 and 4 aircraft.

The results of this study are summarized in Table LXXIV. Expendable heat sink requirements, passive insulation, component weights, fluid routing provisions, and structural considerations are included. The weight of heat transfer loop components are a function of the area cooled and include items such as plumbing and fluid control components. An increase in ECS weight is incurred because of an increase in expendable subsystem requirements.

Table LXXIV Results of Cooled Inlet Studies.

| | | |
|---|---|---|
| Maximum Allowable Interface Temperature (° F) | 250 | 350 |
| Inlet Surface Area Cooled ($ft^2$) | 105 | 172 |
| Reduction in Nacelle Structural Weight (lb)* | -433 | -697 |
| Weight of Heat Transport Loop Components (lb) | +197 | -322 |
| Increase in ECS Weight (lb) (Relative to Study 3 and Study 4 Configurations) | +56 | +170 |
| Total Change in OWE (lb)* | -180 | -195 |
| Total Change in TOGW (lb)* | -672 | -730 |

* Weights are relative to the use of René 41.

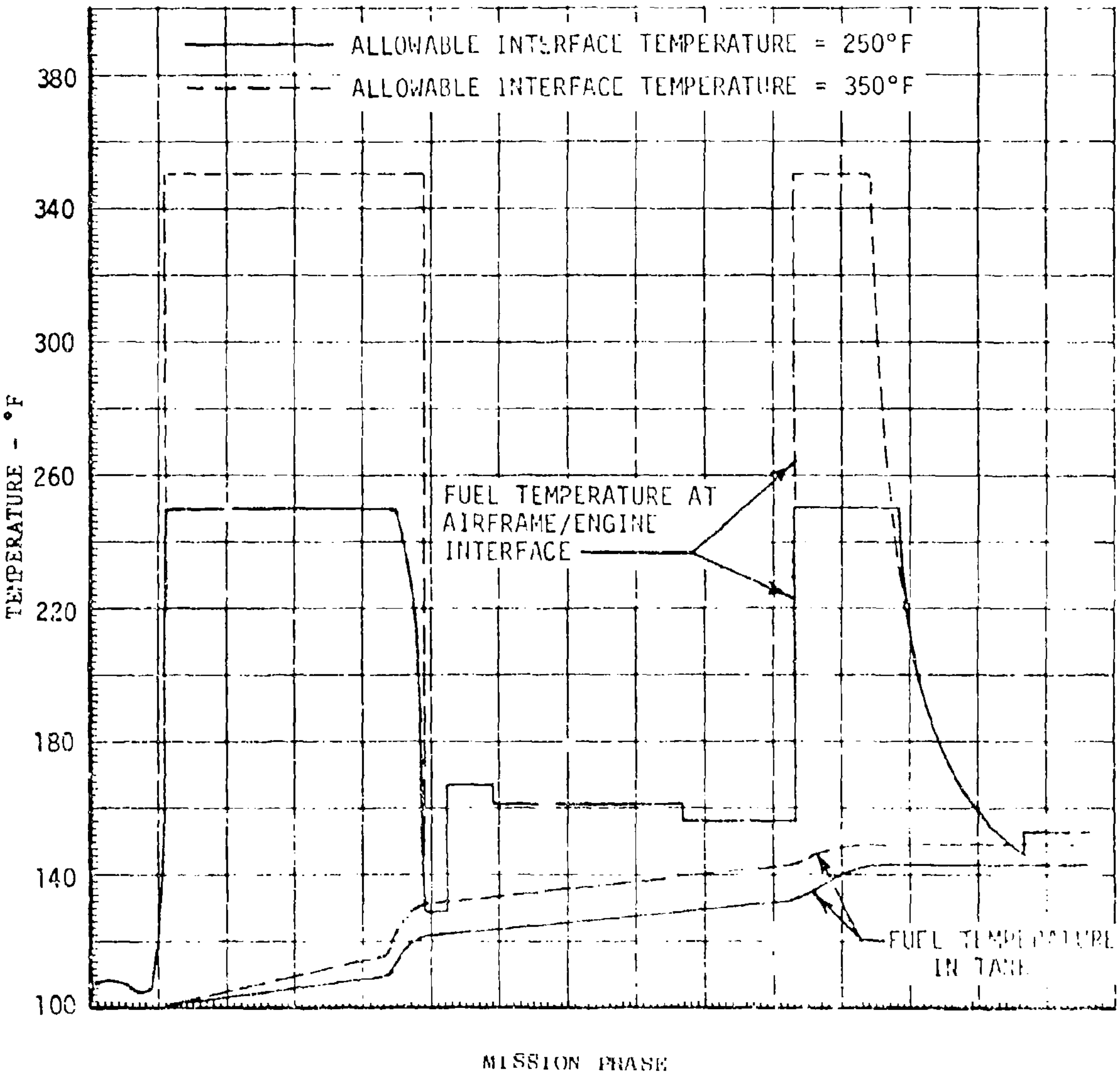



Figure 85. Fuel Temperature Profiles, Cooled Inlet Concept.

# SECTION VI

## INTERCEPTOR PERFORMANCE SENSITIVITIES

The interceptors presented in Section IV represent the basic study results. The sensitivities of the interceptors to changes in design weights, engine performance, mission profile, and aircraft subsystem design philosophy were examined and are presented here.

### A. Design Weight Sensitivities

In order to permit an incremental analysis of the effects of fuel and lubricant properties and system variables on aircraft performance, the sensitivity of TOGW to small changes in fuel density; engine specific thrust and SFC; and the sensitivity of wing area to OWE were determined. These sensitivities can be used independently or in combination to determine changes in interceptor size and weight. They should not be extrapolated beyond the limits of the figures.

#### A.1 Fuel Density Effects

At the inception of this investigation, two fuels were selected to permit evaluation of the effects of fuel thermal limits on engine performance and resulting aircraft size. Since the chosen fuels (JP-5/8 and JP-7) have different average densities (51.8 and 49.7) $lb/ft^3$, respectively), it was decided that the mission should be performed with a constant fuel density of 51.8 $lb/ft^3$. This density is representative of an advanced high stability hydrogenated fuel as well as existing JP-5/8. Should a future high volume demand be established for a high stability fuel, a hydrogenation process will probably be required to meet the demand. This process can be tailored to provide product densities in the neighborhood of 51.8 $lb/ft^3$.

If the fuel density is permitted to vary, the benefits of increased fuel thermal limits can be masked by density effects. As shown in Figure 86, a decrease in fuel density to that of JP-7 would result in an 880 lb increase in TOGW to maintain constant mission performance. This increase in weight results from increased tank size to accommodate the equivalent weight of fuel, which in turn requires an additional increase in fuel requirements and aircraft size/weight.

In order to permit evaluation of a wide range of fuel, Figure 86 encompasses densities from 45 to 55 $lb/ft^3$. It is apparent that future fuels development effort towards the higher densities can prove beneficial in terms of aircraft size. Effort in this area has spawned. However, a balance must be established between allowable fuel cost increment as a function of density and aircraft size. If the aircraft size is reduced, the resulting system cost will also decrease, which can in itself justify a moderate increase in fuel cost with increasing density.

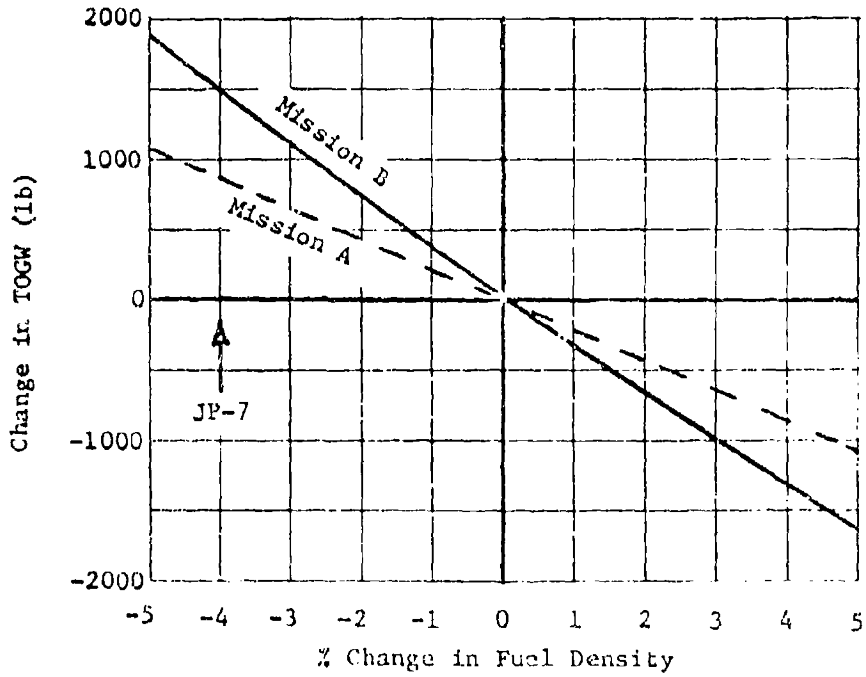



Figure 86. Fuel Density/TOGW Sensitivity.

## A.2 Propulsion Sensitivities

Higher fuel heat sink can permit improved engine performance as realized for both the GE16/FLITE engines and the GE14/FLITE engines. These improvements can be reflected in increased specific thrust and reduced SFC. The TOGW/Specific Thrust sensitivity, Figure 87, and the TOGW/SFC sensitivity, Figure 88 are based on a uniform improvement over the entire baseline mission profile. These sensitivities can be used for first order approximation of the impact of fuel thermal limits on aircraft TOGW as affected by propulsion system characteristics.

## A.3 Operating Weight Empty and Wing Area Effects

The takeoff gross weight sensitivity due to operating weight empty perturbations is presented in Figure 89. The dependence of wing area ($S_W$) on OWE is presented in Figure 90. These sensitivities were determined through perturbations in OWE followed by resizing to the constant baseline mission radius and acceleration time through the use of growth curves. The resulting growth factor is 4.01 (TOGW)/lb (OWE). This configuration has a wing area sensitivity of 23 ft$^2$/1000 lb (OWE).

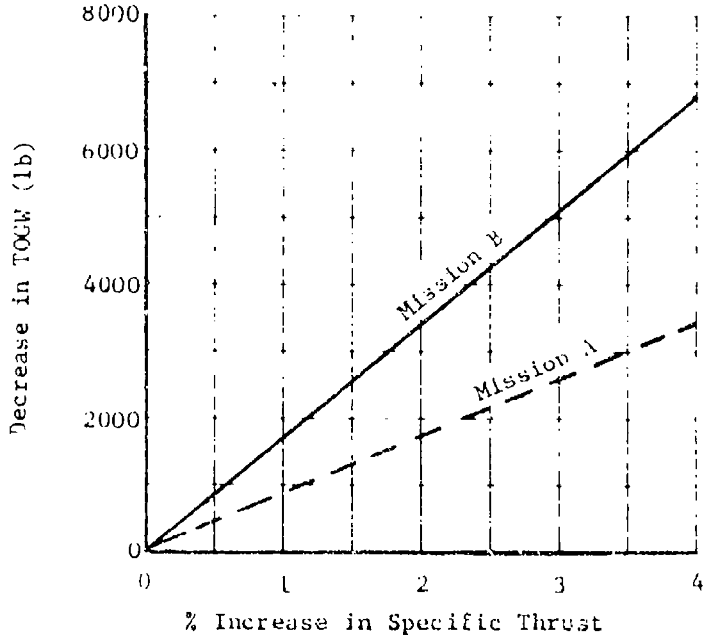



Figure 87. Specific Thrust/TOGW Sensitivity.

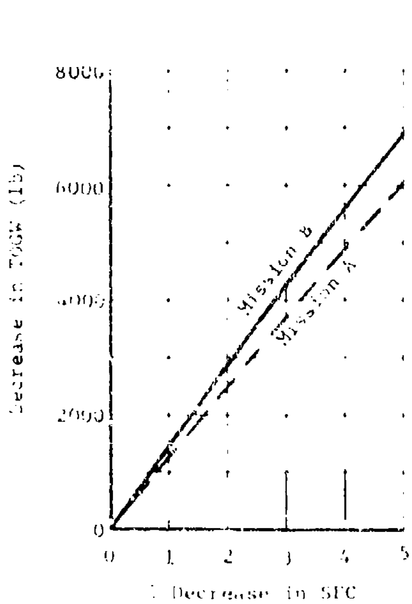



Figure 88. SFC/TOGW Sensitivities.

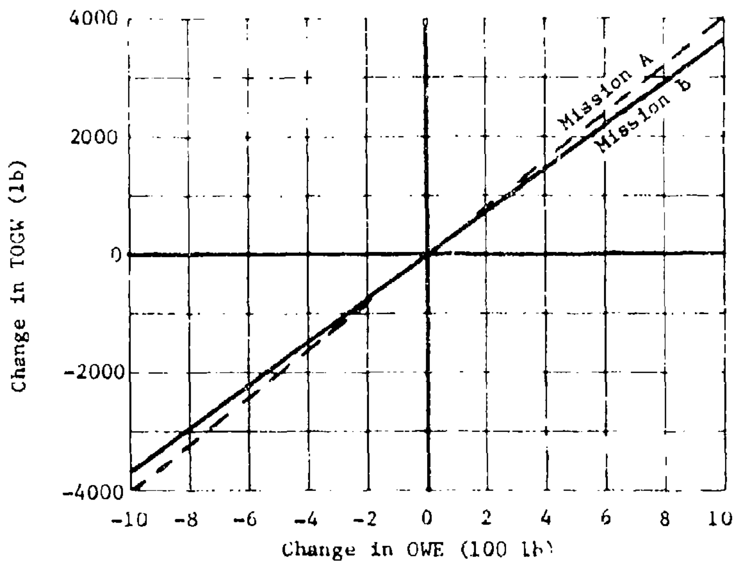



Figure 89. Operating Weight Empty/TOGW Sensitivities.

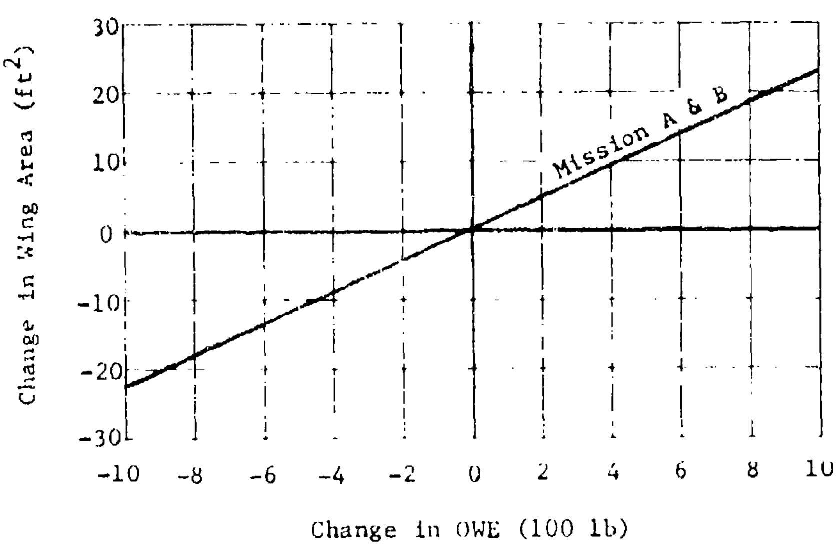



Figure 90. OWE/Wing Area Sensitivity.

# SECTION VII

## CONCLUSIONS

Two mission profiles were defined and investigated, one for a Mach 3+ interceptor and the other utilizing an interceptor with Mach 4+ capability. Two thermodynamic classes of fuels, JP-4/5/8 and JP-7 were studied along with four fluids used in both the lubrication and fluid power system, MIL-L-27502, a hypothetical 500° F ester, polyphenyl ether and perfluorinated polyether. The results were measured in terms of engine weight, engine performance improvement and aircraft takeoff gross weight.

The primary conclusions are:

- JP-5/8 fuel and MIL-L-27502 lubricant/hydraulic fluid are recommended for the Mach 3+ interceptor while a fuel with JP-7 thermal stability and a 500° F ester lubricant/hydraulic fluid are recommended for the Mach 4+ interceptor.

- For the range of temperatures investigated, both the Mission A and B interceptors benefit from increasing interface fuel temperatures.

- Higher thermal stability fuels are thermodynamically feasible for improving engine performance when used in fuel/air heat exchanger systems.

- On a bulk oil temperature basis the capability of MIL-L-27502 is considered to be the minimum necessary to satisfy Mach 3+ and Mach 4+ advanced military system requirements. Above this level the influence of bulk oil temperature has only secondary influence on interceptor performance.

- Use of precooled fuel provides an attractive option to achieve a direct reduction in aircraft size and weight.

  - Mission A (Mach 3+) - Thermal stability of JP-5/8 fuels appears adequate, only minor performance improvements associated with higher stability fuels.

  - Mission B (Mach 4+) - Thermal stability of JP-5/8 class fuels allows marginal operation (with degraded performance). Higher stability fuels (JP-7 class) enables significant performance improvement for the combination cycle engines.

The fuels and lubricants studied in the program can all satisfy the Mission A and Mission B heat sink requirements, however the lower temperature combinations require increased system complexity and weight. The Mach 3+ mission can be adequately performed using JP-5/8 fuel and MIL-L-27502 lubricant and hydraulic fluid without incurring severe penalties to either engine or aircraft system design and performance. Mission B can be performed with JP-5/8, but fuel temperatures exceeding the current unlimited service thermal stability limit of 325° F to approximately 500° F provides adequate margin for the Mach 4+ interceptor. A 500° F bulk oil temperature capability also provides acceptable lubricant/hydraulic fluid performance.

The lightest weight aircraft were obtained using JP-7 fuel for both Mission A and Mission B. The elevated thermal stability of JP-7 permits additional heat sink utilization concepts to be incorporated into the aircraft/engine designs, improving engine performance and reducing aircraft ECS weight and complexity. These performance improvements become significant when fuel temperature levels approaching current research values (1000° F) are utilized. When maintainability, reliability and life become factored into an actual interceptor configuration, the use of JP-7 may also be considered as being more desirable.

Both the Mission A and B interceptors benefit from increasing interface fuel temperatures. Advantages gained in increasing the airframe heat sink allotment offset the reduction in engine performance caused by the removal of the LP turbine cooling air cooler from the GE16/FLITE-1C engines. For Mission B, the engine performance increases with increasing interface temperature. This reflects the increase in combustor efficiency and the ability to use the ramburner liner cooling air fuel/air coolers at the higher interface temperatures.

The definition of an LP turbine fuel/air heat exchanger for the GE16/FLITE-1C engine and the design of the ramburner liner cooling air fuel/air cooler for the GE14/FLITE-2D engine established the thermodynamic feasibility for heat exchanger systems to improve engine performance. Much further work needs to be done, however, in establishing the design and performance criteria for actual system designs.

From an incremental bulk temperature basis the candidate lubricants with the exception of perfluorinated polyether have only secondary influence on interceptor performance. Significant weight increases were obtained with the perfluorinated fluid due to its low bulk modulus and high vapor pressure. Beyond this, however, differences in bulk oil temperature capability above a minimum level as defined by MIL-L-27502 (425° F) were not of enough significance to permit a clear-cut lubricant/hydraulic fluid decision. The recommended lubricant/hydraulic fluids of MIL-L-27502 and 500° F ester for Mission A and Mission B respectively were selected when the other factors affecting system operation such as operational service life, hot spot stability and vapor pressure were considered.

An attractive design option in terms of interceptor size and weight is through the use of precooled fuel. The use of this technique in supplemental studies for both Mission A and Mission B produced significantly lighter interceptor designs.

And finally, the key factor to the future success of advanced aircraft/engine systems is the integrated systems approach to thermal management. Close cooperation between the engine and airframe manufacturers is mandatory if these systems are to achieve a high level of efficient operation while still incorporating current or near-term fuels, lubricants, and hydraulic fluids. The airframe/engine system integration concepts graphically demonstrated in this program should be applicable to all future programs, not just those involving high flight speeds.

## SECTION VIII

## RECOMMENDATIONS

Determination of performance effects on an installed engine basis (airplane performance increments for a fixed mission design) enables evaluation of existing fuel and lubricant capabilities. Payoffs for research and development alternatives are identified on a relative performance basis. It is recommended that development in the following areas be pursued:

- o Higher density and lower cost alternatives to achieve JP-7 class thermal stability.
- o A 500° F bulk oil temperature capability lubricant.
- o High temperature fluid system components.
- o Electronic control systems.
- o High temperature fuel/air heat exchangers.
- o Aircraft/engine thermal management practices for near-term applications.
- o Operational and performance implications of precooled fuel.

With the technology assumptions for the mid 1980 time period, JP-5/8 fuel was found to be adequate for Mission A and only small weight reductions were achieved by using the higher stability JP-7. However, due to possible limitations in the areas of maintainability, reliability, and life and due to the marginal nature of JP-5/8 in the Mission B application, development of a higher density high stability fuel is recommended. A thermal stability greater than 700° F and a density greater than 51.8 $lb/ft^3$ can potentially be achieved through low cost refinery processing of kerosene fractions. The cost of the fuel is considered to be of primary importance if the benefits of higher thermal stability are to be translated into reduction in aircraft/engine program costs.

During the FLITE Program it was found that lubricants with bulk oil temperature capabilities of 500° F provided acceptable lubrication system performance. Oil temperature capabilities below this value tended to produce increased degradation effects and decreased service life of the lubricant while the performance gains for higher bulk oil temperature capabilities were negligible. For these reasons development of a 500° F lubricant is recommended. In addition the other lubricant properties such as viscosity, autoignition temperature, and vapor pressure would need to be factored into the investigation.

Satisfactory operation of fuel delivery and fluid power system components have been proven with the present primary type JP4, JP5, Jet-A and Jet-B fuels, and MIL-L-7808 and MIL-L-23699 hydraulic fluids on present operational type aircraft. However, it should be noted that fluid pumping and metering for these present engine fluids is being accomplished at temperature levels below the 325° F maximum limit for the fuels and 425° F maximum bulk oil temperature for hydraulic fluids. Although some component experience at elevated temperatures was achieved during the XB70 and SST engine programs, the high temperature fluids and the operating environments of the GE16/FLITE and the GE14/FLITE engines would require significant component development effort. In the early stages of initial concept, therefore, it is recommended that scale or subcomponent tests be performed on system components within the expected fluid temperature ranges and simulated environments. These tests will develop the accuracy, temperature, compensation, control stability criteria, and volumetric metering characteristics required for the fuel delivery and fluid power systems. It is anticipated that scale or component tests will also establish shaft seal, bellows, dynamic piston, and static seal designs for the systems.

Precise, responsive control of engine thrust is a prime requirement for the GE16/FLITE-1 and GE14/FLITE-2 types of engines. Operation in critical Mach temperature areas and integration with the aircraft systems may require a greater degree of complexity than in existing designs. Continued investigation of electronic control systems compatible with the anticipated temperature environments is recommended.

One of the primary reasons for the significant weight reductions achieved through the use of JP-7 in Mission B was the incorporation of the ramburner liner cooling air fuel/air coolers. These heat exchangers were located immediately upstream of the ramburner distribution manifolds. These heat exchangers permit a 50 percent reduction in cooling air needed for the ramburner liner and the exhaust nozzle. To gain this increased engine performance, however, it was necessary to allow high temperature peaks approaching 1000° F. Although the design and location of the heat exchangers minimize the residence time at these temperatures, little is known about the properties or the performance of JP-7 at these conditions. It is recommended that programs of fuel property definition and heat exchanger design and performance at elevated temperature conditions be further explored.

Both Mission A and B interceptors benefit from increasing interface temperatures. Advantages gained in increasing airframe fuel heat sink allotment have offset any reduction in engine performance for Mission A. For Mission B, the engine performance increased with increasing interface temperature due to improved engine cycle thermal efficiency. Recommendations concerning engine/airframe fuel interface temperature include an assessment of current design practices and system specifications which limit the interface temperature to approximately 200° F. The present generation of military aircraft are approaching the limits of these current guidelines, requiring an alternate systems (engine and airframe) design approach for the continued use of high availability JP-4/5/8 type fuels.

Application of thermal management from an aircraft/engine integrated systems approach could enable quantification of the limits of existing fuels and lubricants as applied to near term evolutionary aircraft designs. This could pave the way for improved performance resulting from increased use of fuel to satisfy aircraft system heat loads. The evaluation and comparison of the overall performance effects resulting from variations in the allocation of fuel heat sink should be identified along with the effects of systems and fluids technology improvements. The major objective of such a program would be to formulate guidelines for future aircraft/engine fuel system designs which would stress an integrated approach to maximize installed systems performance and to provide a basis for uniform, compatible engine and airframe specifications revisions.

An attractive design option in terms of interceptor size and weight is the use of precooled fuel. The overall effects of precooled fuel on vehicle performance have been identified in terms of reduced aircraft and ECS weight/complexity; however, other factors should be investigated to develop a complete understanding of the advantages and drawbacks of this concept. A slight increase in fuel cost would result from the precooling operation together with increased ground support equipment. These cost increments must be evaluated against the reduced total program costs resulting from the aircraft size reduction and aircraft subsystems simplification. Previous investigations of a similar nature have indicated the desirability of reduced size and complexity at the expense of increased ground support. An investigation of these parameters with application potential to near term military aircraft systems is strongly recommended.

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